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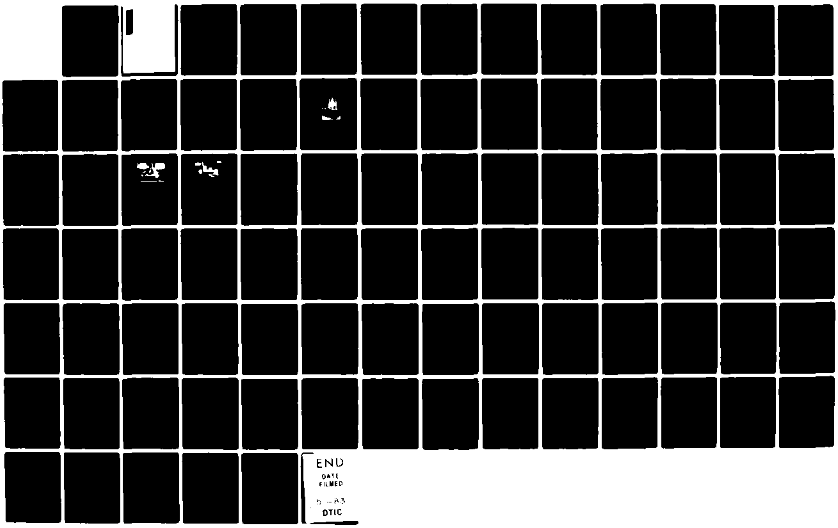

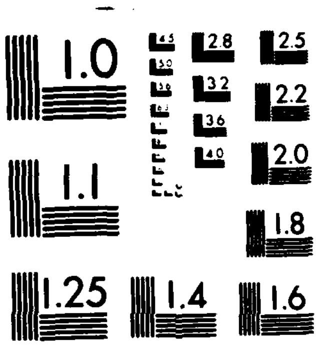

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A problem inherent in many standard test methods in materials engineering is the preparation of a representative or standard specimen. The Marshall Test, ASTM D 1559-76, "Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus," is subject to variability introduced by nonstandard specimens. Standard sized specimens are compacted at specified temperatures using standard equipment and procedures. This study investigated the effects of variations in specimen size, specifically specimen height, on Marshall stability and flow. In order to determine the adequacy

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Block #20, ABSTRACT Continued

of accepted correction methods, the observed variability introduced by nonstandard specimen heights was compared to the accepted correction method. Recommendations concerning the correction of stability and flow values resulting from nonstandard specimens are presented.

The Effects of Variations in Specimen Height on the Marshall Properties of Asphaltic Concrete

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Final Report 14 Dec 82

A thesis submitted to Clemson University, Clemson, South Carolina in partial fulfillment of the requirements for the degree of Master of Science Civil Engineering.

December 14, 1982

To the Graduate School:

Herewith is submitted a thesis written by Robert Foster Webb entitled "The Effects of Variations in Specimen Height on the Marshall Properties of Asphaltic Concrete." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

James L. Burati, Jr.
Thesis Advisor

We have reviewed this thesis
and recommend its acceptance:

Herbert W. Busching

Hoke S. Hill, Jr.

Accepted for the Graduate School:

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THE EFFECTS OF VARIATIONS IN SPECIMEN HEIGHT ON THE MARSHALL PROPERTIES OF ASPHALTIC CONCRETE

A Thesis

Presented to

the Graduate School of

Clemson University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Civil Engineering

---

by

Robert Foster Webb

December 1982

ABSTRACT

The effects of variations in specimen height on the values obtained for stability and flow using the Marshall test procedure were investigated. While Marshall testing procedures specify standard specimens of 2.5 inches in height, specimens which differ from the standard height are often prepared. These differences in specimen height are an additional source of variability in the test procedure.

Current literature recognizes a correction procedure to be applied to stability readings obtained from nonstandard sized specimens. This correction procedure is based on a linear stability response to changes in specimen height. A correction procedure for flow is not currently used nor is a dependent relationship of flow to height recognized.

The objective of this study was to determine the effects of variations in specimen height on stability and flow values and to assess the adequacy of current practices dealing with this variability.

Five samples of asphaltic concrete were tested for the effects of specimen height on Marshall stability and flow readings. For each sample, specimens were prepared with heights varying from 2.0 to 3.0 inches. A linear regression analysis was performed for both stability and flow using specimen height as the independent variable.

In the case of both stability and flow, a high correlation with specimen height was observed to exist. For stability, the linear regression line that was obtained from laboratory observations differed from the relationship suggested by the published correction method.

This difference was statistically significant. For flow, the regression coefficient proved to be statistically significant, indicating the existence of a specimen height effect on flow readings.

The findings concerning stability indicated that the currently recognized correction method requires adjustment. A correction method consistent with experimental results was recommended. The findings concerning flow indicated the need to implement a correction method. Such a correction method for flow was recommended.

ACKNOWLEDGEMENTS

I would like to express my appreciation to my advisory committee for their leadership and assistance in the preparation of this report. Dr. James L. Burati, Jr., Chairman, provided guidance on all phases of the investigation and reviewed the report manuscript. Dr. Herbert W. Busching assisted in a search of background information and advised on the engineering aspects of the report. Dr. Hoke S. Hill, Jr. advised on the experimental design of the investigation and the statistical analysis of data.

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CHAPTER I

INTRODUCTION

Background

The Marshall method of design for asphalt paving mixtures was originally developed by the late B.G. Marshall, a materials engineer with the Mississippi State Highway Department. His concepts were modified by the U.S. Army Corps of Engineers Waterways Experiment Station which conducted extensive research immediately after the conclusion of World War II with the intent of alleviating some of the problems that were experienced by construction engineers during that conflict. Their objective was to devise a simple method whereby an asphalt mixture could be designed and controlled during construction with confidence that it would be satisfactory for the intended service loads. This work, published in 1948, resulted in a standard field portable test apparatus, standardized test procedures, and design criteria obtained from correlating the performance of pavement test sections with the laboratory Marshall properties of the pavement mixtures (1).

The Marshall test method has since been adopted by many state and federal engineering agencies as the standard method for the design and control during construction of asphaltic concrete pavements. The Marshall method has been standardized under the auspices of various state and federal agencies, the American Society for Testing and Materials (ASTM), and the Asphalt Institute (2,3,4,5,6).

In general, the Marshall method prescribes a standard procedure for the preparation of test specimens and a standard test procedure yielding values for five test properties. The test properties are:

1. unit weight of the compacted mix,
2. percentage of voids in the mineral aggregate (VMA) in the compacted mix,
3. percentage of air voids in the compacted mix,
4. stability, and
5. flow.

The stability and flow values are obtained by loading the specimen to failure at a constant rate of deformation of 2.0 inches per minute. A standard testing head apparatus is used to transmit the load to the specimen. The stability value is the maximum load applied to the specimen before failure and is measured in pounds.

Flow, measured in units of 0.01 inch, is the amount of deformation imposed on the specimen from the initial application of load to failure. Failure is defined as the maximum load. The Marshall testing apparatus is shown in Figure 1.

The unit weight and voids values are obtained mathematically by performing a weight and volumetric analysis on the compacted specimen and its components. This procedure is explained in "The Standard Test Method for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens", ASTM D2726 (7).

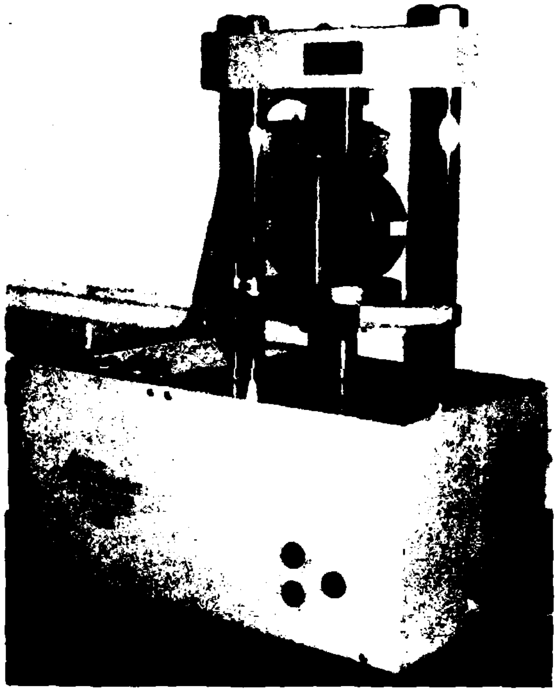


Figure 1. Marshall Testing Apparatus Used in the Experiment

Statement of the Problem

A problem inherent in the Marshall method is the preparation of a standard sized specimen. The standard specimen is a cylinder 2.5 inches in height with a 4.0 inch diameter. Specimens are compacted in molds that provide the correct 4 inch diameter. However, the height is dependent upon the amount of material introduced into the mold. Since the compacted bulk density of the material is variable and often unknown, the amount of material required to produce a standard specimen is similarly variable. This causes nonstandard sized specimens to be prepared. In some instances, particularly in quality control applications, data obtained from nonstandard specimens must be utilized. Also, when pavement cores are tested, it is often not possible to obtain 2.5 inch specimens because of the pavement thickness. Clearly, the use of test data obtained from nonstandard specimens for the purpose of comparison with specifications and as an appraisal of material properties introduces a source of error with a potential detrimental effect on mix design and quality control.

Currently, standardized procedures call for the adjustment of stability readings taken from nonstandard specimens. There is no correction procedure for flow readings taken from nonstandard specimens.

Objectives

The purpose of this study was to investigate the effects of variations in specimen height on Marshall test results. Specifically, the following objectives were addressed:

1. Estimate the effect of height on the stability and flow test values for specimens of variable heights over a feasible range.

2. Compare the effect of variations in specimen height on the stability response observed in laboratory testing with the effect corresponding to the published stability correction procedures.

3. Test the observed effects of height on stability and flow for statistical significance and make recommendations concerning the adequacy of current stability correction procedures and the advisability of implementing flow correction procedures.

CHAPTER II

CURRENT CORRECTION PROCEDURES

Background

The possibility of a height effect causing a distortion of Marshall test values has received scant attention. The stability correction procedure which features "correlation ratios" that are published in tabular form with corresponding heights originated in the developmental report by the Corps of Engineers (1). That report contains only an explanation of the correction procedure and does not explain the development of the correlation ratios or the basis of their use. It also dismisses the possibility of a significant height effect on flow by stating, "A correction factor for flow is not necessary" (1). There is no evidence to support that assertion. A literature search and discussions with researchers familiar with the development of the Marshall test failed to recover the basis for the stability correlation ratios or the apparent dismissal of a significant height effect on flow.

Explanation of the Stability Correction Procedure

The stability correlation ratios are universally recognized by engineering agencies that employ the Marshall method. This correction procedure requires the determination of the actual specimen height. The corresponding correlation factor is then multiplied by the measured stability reading to determine the corrected stability value. These correlation ratios are presented in Table I. In practice, the appropriate correlation factor is usually determined by matching the actual

volume of the specimen to the corresponding volumes in the table. This approach compensates for the irregularity of the specimen height that is often measured.

Analysis of Stability Correlation Ratios

In an effort to discern the physical relationship between specimen height and stability that corresponds to the published correlation ratios, an analysis of the correlation ratios as a function of specimen height was conducted. A plot of the correlation ratios as a function of height revealed a curve that could only be explained by a complex equation. A plot of the correlation ratios is presented in Figure 2.

Further consideration of the problem led to an analysis of the inverse of the correlation factors as a function of height. A linear regression procedure performed over the range of 1.0 to 3.0 inches revealed a regression line with a coefficient of determination of 0.992 and a significant regression coefficient of 0.568. The inverse correlation ratios are presented in Table II. A graph of the inverse correlation ratios is presented in Figure 3. This figure confirms that the inverse correlation ratios approach a linear function. A break in the slope of the function occurs at a specimen height of 1.5 inches. It is significant that the region above 1.5 inches has a constant slope because it is relevant to actual practice. The region below 2.0 inches has little practical application and was not considered in the experimental phases of this study.

From the analysis of the inverse correlation ratios, it was concluded that the correlation ratios were representative of a relationship in which the stability response was a linear function of specimen

Table I. Stability Correlation Ratios as Published by the Asphalt Institute (2)

Volume of specimen (cu cm)	Height (in)	Correlation Ratio
200-213	1	5.56
214-225	1 1/16	5.00
226-237	1 1/8	4.55
238-250	1 3/16	4.17
251-264	1 1/4	3.85
265-276	1 5/16	3.57
277-289	1 3/8	3.33
290-301	1 7/16	3.03
302-316	1 1/2	2.78
317-328	1 9/16	2.50
329-340	1 5/8	2.27
341-353	1 11/16	2.08
354-367	1 3/4	1.92
368-379	1 13/16	1.79
380-392	1 7/8	1.67
393-405	1 15/16	1.56
406-420	2	1.47
421-431	2 1/16	1.39
432-443	2 1/8	1.32
444-456	2 3/16	1.25
457-470	2 1/4	1.19
471-482	2 5/16	1.14
483-495	2 3/8	1.09
496-508	2 7/16	1.04
509-522	2 1/2	1.00
523-535	2 9/16	0.96
536-546	2 5/8	0.93
547-559	2 11/16	0.89
560-573	2 3/4	0.86
574-585	2 13/16	0.83
586-598	2 7/8	0.81
599-610	2 15/16	0.78
611-625	3	0.76

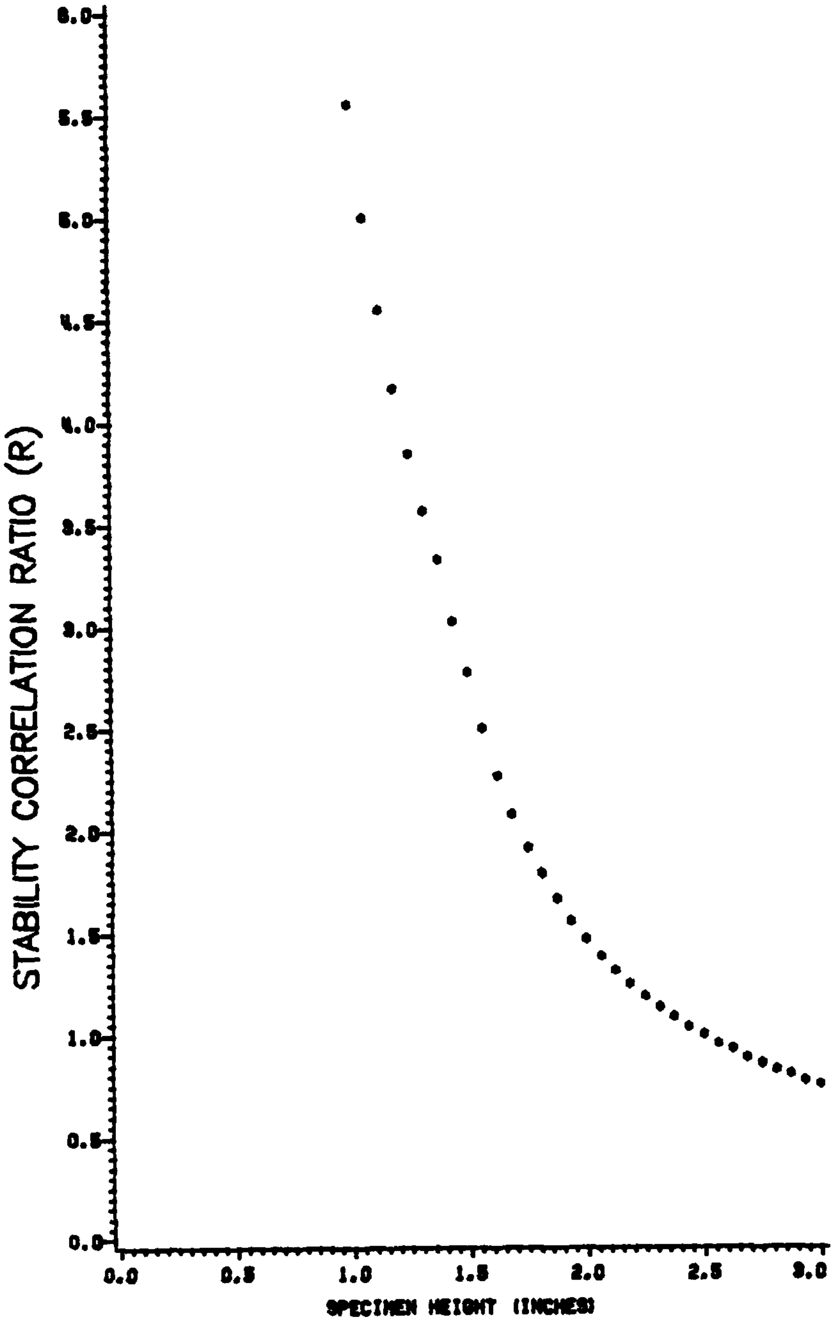


Figure 2. Stability Correlation Ratios as Published by the Asphalt Institute

Table II. Inverses of Stability Correlation Ratios (2)

Height (in)	Inverse Correlation Ratio
1	0.17986
1 1/16	0.20000
1 1/8	0.21978
1 3/16	0.23981
1 1/4	0.25974
1 5/16	0.28011
1 3/8	0.30030
1 7/16	0.33003
1 1/2	0.35971
1 9/16	0.40000
1 5/8	0.44053
1 11/16	0.48077
1 3/4	0.52083
1 13/16	0.55866
1 7/8	0.59880
1 15/16	0.64103
2	0.68027
2 1/16	0.71942
2 1/8	0.75758
2 3/16	0.80000
2 1/4	0.84034
2 5/16	0.87719
2 3/8	0.91743
2 7/16	0.96154
2 1/2	1.00000
2 9/16	1.04167
2 5/8	1.07527
2 11/16	1.12360
2 3/4	1.16279
2 13/16	1.20482
2 7/8	1.23457
2 15/16	1.28205
3	1.31579

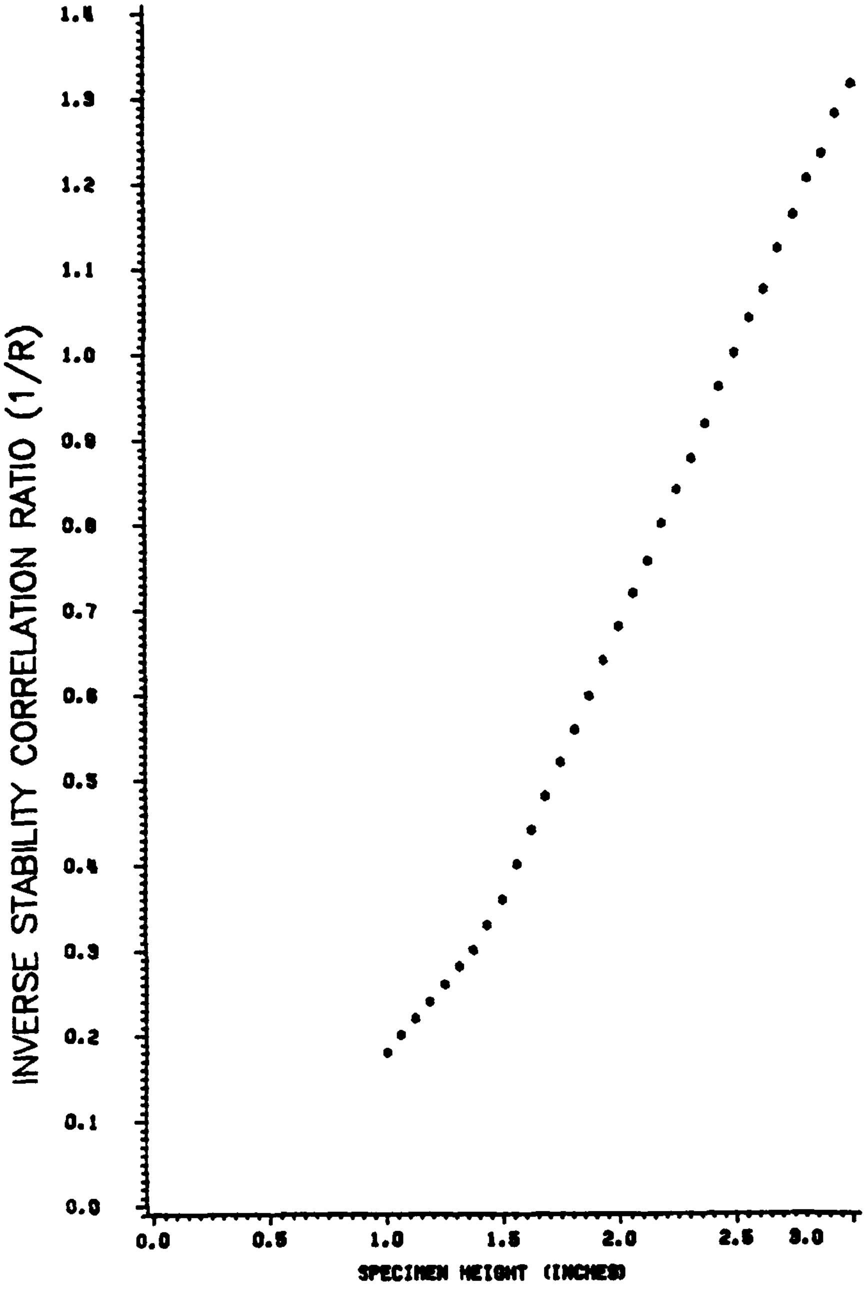


Figure 3. Inverses of the Stability Correlation Ratios

height. In effect, the correlation ratios, (R), were the ratio of the standard stability value for a specimen of 2.5 inches (S_{std}) to the actual stability value reading at any height x, (S_x), or

$$R = S_{std}/S_x.$$

Limitations on Specimen Height

A review of the standardized procedures that have been published by the various state and federal engineering agencies revealed that most tables of stability correlation ratios are provided with specimen heights from 1.0 to 3.0 inches. One document, MIL-STD-620A, "Military Standard Test Methods for Bituminous Paving Materials" (3), covered the range from 1.0 to 3.25 inches. However, the procedures of the Federal Aviation Administration (4) and the South Carolina State Highway Department (6) limited the range to the interval from 2.0 to 3.0 inches. It should be noted that the actual correlation ratios presented by all of the agencies were identical.

The dimensions of the Marshall testing head and compaction mold were observed to be an influence on the allowable specimen height. A diagram of the testing head appears in Figure 4. The testing head width is 3.0 inches. This limitation caused specimens with heights greater than 3.0 inches to protrude past the sides of the testing head. This condition prevented the applied load from being distributed over the entire thickness of the specimen, causing a variation in the conditions of the Marshall procedure.

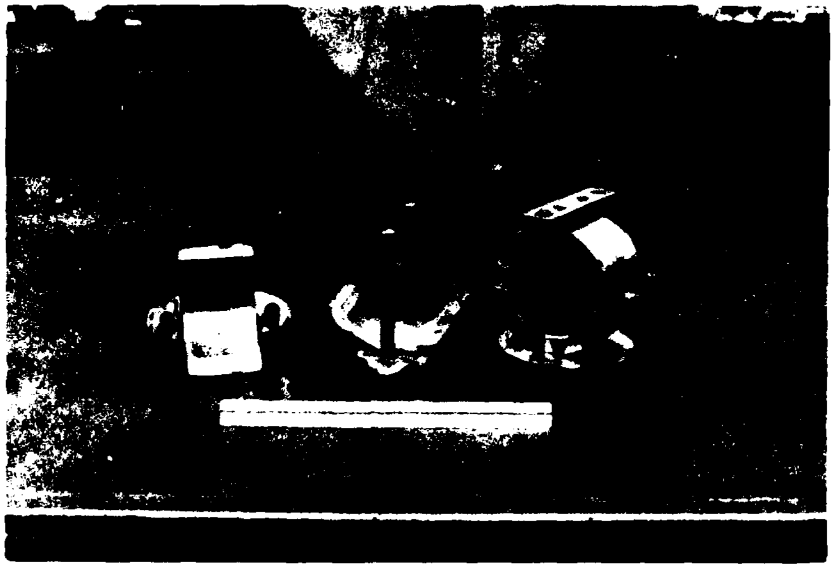
It was also observed that the compaction molds were 3.0 inches deep. A diagram of the compaction mold appears in Figure 5. While specimens could be compacted with heights in excess of 3.0 inches, they

tended to be of poor quality with a flange on one side that created a nonuniform diameter. Laboratory observations showed that such oversize specimens tended to produce excessively low stability and high flow values relative to specimens that were under the 3.0 inch height limit.

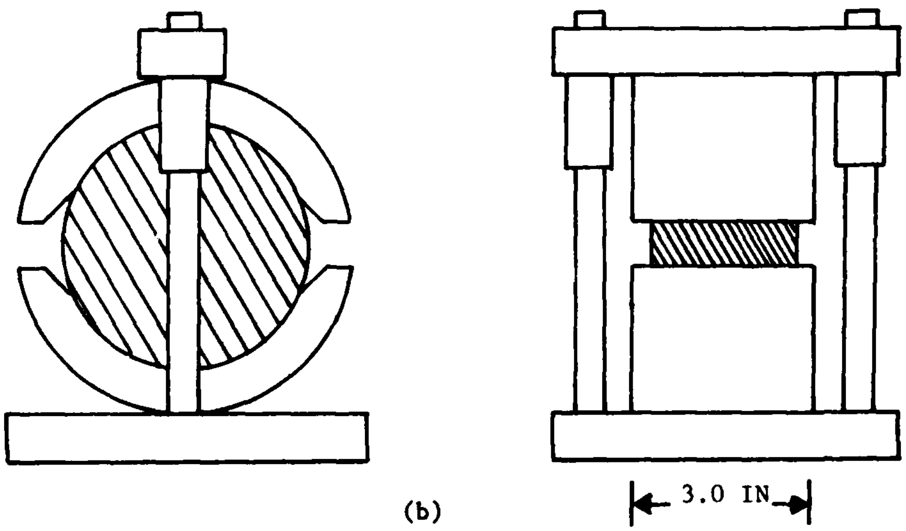
Knowledge of the process used to prepare specimens and discussions with laboratory technicians led to the conclusion that it was appropriate to limit the investigation to specimen heights in the interval from 2.0 to 3.0 inches. This provision for a tolerance of one half inch around the standard was seen to be a reasonable standard for the properly trained technician.

Derivation of Stability Correlation Parameters

Considering the correlation ratios over the limited range of feasible specimen heights, the slope of the line defined by the inverses of the correlation factors was 0.6405 with an intercept of -0.6016. This was computed using a linear regression analysis. The coefficient of determination for this relationship was 0.999784, approaching a perfect correlation. These parameters were used to define the physical relationship between height and the published stability correlation table. Figure 3 demonstrates the linearity of the inverse correlation ratio function in the interval from 2.0 to 3.0 inches.



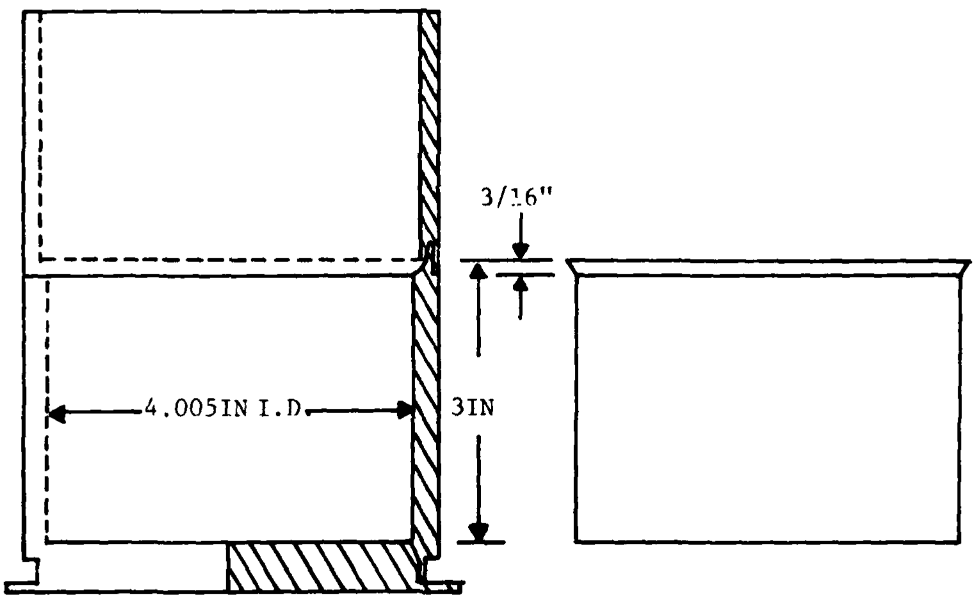
(a)



(b)

Figure 4. Marshall Testing Head, (a) Photograph of Marshall Testing Head Components, (b) Diagram of Assembled Testing Head

(a)



MOLD ASSEMBLY (b) OVERSIZED SPECIMEN

Figure 5. Marshall Specimen Compaction Mold, (a) Photograph of Compaction Mold Components, (b) Diagram of Mold Assembly and an Oversize Specimen Exhibiting a Flange on the Top Edge

CHAPTER III

EXPERIMENTAL PROCEDURES

An experimental design intended to meet the objectives of the study using linear regression analysis was developed. Specimens of varying heights from 2.0 to 3.0 inches were prepared under controlled conditions in accordance with standard Marshall test procedures. The bulk specific gravity and volume of the specimens were determined. Stability and flow tests were performed. A linear regression analysis with stability and flow as dependent responses to specimen height was conducted. This produced regression lines that could be used to estimate the effect that variations in specimen height had on stability and flow readings for the mix under study. The experiment was conducted five times on different mixes. For each experiment, approximately 33 specimens of varying heights were prepared and tested.

Description of the Material Tested

The asphaltic concrete tested was obtained from commercial hot-mix plants located close to the laboratory facility at Clemson, South Carolina. Plants at Liberty and Anderson, South Carolina were operated by Sloan Construction Company of Greenville, S.C. Another plant at Anderson was operated by Harold A. Pickens and Sons Construction Company of Anderson.

In all cases, the material was sampled from a truck immediately after loading. The sampling was conducted in accordance with ASTM D979, "Sampling Bituminous Paving Mixtures" (8). The total sample weighed

approximately 100 pounds with a temperature of approximately 310 degrees Fahrenheit when it was shoveled from the truck and placed in buckets. The material was transported to the laboratory where it was placed in a heated oven. The transit time from the plants to the laboratory ranged from 30 to 45 minutes. Upon arrival at the laboratory, the temperature was approximately 300 degrees. The material was maintained at a temperature of 280 degrees in an oven until it was removed and placed into the compaction mold.

In all cases, the asphaltic concrete was sampled from material that was produced as a surface or binder course for a South Carolina Department of Highways and Public Transportation (SCDHPT) contract subject to statistical quality control. A description of the samples is presented in Table III.

Job mix formulas for the mixes tested are given in Table IV. A description of the component materials incorporated in the mixes is presented in Table V. In all cases, the mineral aggregate consisted of crushed granite that was produced locally. The type of mix refers to SCDHPT designations (9). The applicable SCDHPT type specifications are presented in Table VI.

Compaction Procedure

The compaction procedure that was utilized was designed to produce 33 specimens of each mix while minimizing the introduction of experimental errors that might bias the test results. The goal was to have the frequency of the specimens uniformly distributed over the range of heights being considered.

Table III. Summary of Materials Sampling Information

Mix	Source	Sample Date	SCDHPT Mix Type	Aggregate Source	Plant Type
1	Sloan/ Anderson	6/15/82	3 Surface	Anderson	8000 lb batch
2	Pickens/ Anderson	6/23/82	2 Surface	Liberty	300 tph drum
3	Sloan/ Liberty	6/30/83	3 Surface	Liberty	10,000 lb batch
4	Sloan/ Anderson	7/6/82	2 Binder	Anderson	8000 lb batch
5	Pickens/ Anderson	7/13/82	1 Binder	Liberty	300 tph drum

Table IV. Job Mix Formulas for the Five Mixes Tested

Mix	1	2	3	4	5
Sieve	Percent Passing By Weight				
3/4 in	100	100	100	95	100
1/2 in	98	98	98	70	99
3/8 in	94	93	93		80
No. 4	68	62	71	40	39
No. 8	54	49	58	32	29
No. 30	33	31	35		
No. 100	13	13	13		
NO. 200	6	6	6		
Asphalt Cement, percent of total mix by weight	6.2	5.7	6.2	5.2	5.0

Table V. Description of the Materials Used in the Asphaltic Concrete Mixtures

Component	Description	Job Mix	Specific Gravity
(a) Mix 1: Aggregate, crushed granite			
Coarse	1/2 in crusher run	100 *	2.66
Asphalt	AC 20	6.2 **	1.03
(b) Mix 2: Aggregate, crushed granite			
Coarse	No. 789 stone	40 *	2.67
	1/2 in asphalt sand	45 *	2.67
Fine	manufactured sand	15 *	2.67
Asphalt	AC 20	5.7 **	1.03
(c) Mix 3: Aggregate, crushed granite			
Coarse	No. 789 stone	20 *	2.67
	1/2 in asphalt sand	60 *	2.67
Fine	manufactured sand	20 *	2.67
Asphalt	AC 20	6.2 **	1.03
(d) Mix 4: Aggregate, crushed granite			
Coarse	1 in crusher run	80 *	2.66
Fine	1/2 in crusher run	20 *	2.66
Asphalt	AC 20	5.2 **	1.03
(e) Mix 5: Aggregate, crushed granite			
Coarse	1/2 in crusher run	55 *	2.67
Fine	1/2 in asphalt sand	45 *	2.67
Asphalt	AC 20	5.0 **	1.03

* Percent of aggregate by weight

** Percent of total mix by weight

Table VI. Standard Specifications for Applicable South Carolina Surface and Binder Courses (9)

	Type 2 Surface	Type 3 Surface	Type 1 Binder	Type 2 Binder
(a) Mineral aggregate				
sieve		Percent Passing By Weight		
1 in				100
3/4 in	100	100	100	88-100
1/2 in	97-100	97-100	95-100	57-88
3/8 in	80-100	80-100	60-98	
No. 4	55-75	58-78	30-68	30-52
No. 8	35-50	42-64	18-36	20-36
No. 30	18-32	18-40		
No. 100	8-16	5-20		
No. 200	3-8	2-8		
(b) Asphalt cement, percentage of total mixture by weight				
	4.8-6.8	4.8-6.8	4.0-6.0	3.5-5.5
(c) Minimum stability, lbs				
	1250	600	800	1000
(d) Air Voids, percent				
	3-6	3-7	--	--

For each mix, it was assumed that the weight of a standard specimen was 1200 grams. This translated to 480 grams per inch of height, allowing the boundary weights of 960 grams and 1440 grams, corresponding to 2.0 and 3.0 inches, respectively, to be calculated. This weight interval was divided into evenly distributed increments of 16 grams, providing 31 target weights. Additionally, 2 target weights outside the 1440 gram boundary were designated in order to decrease the possibility of leaving a gap in the specimen height interval in the vicinity of 3.0 inches in case of an inaccurate weight to height assumption. The resulting target weights are presented in Table VII.

Specimens of the various target weights were prepared in random order. This was done in an effort to minimize the effect of inconsistencies in the mix and the possible effects of time on the experiment. It was felt that randomization would cause any such error to equally affect the Marshall properties of the specimens at all heights, thereby minimizing the possiblility of the introduction of bias.

While 33 specimens of each mix was the goal, it was sometimes exceeded and once was not attained. The goal was exceeded when sufficient material from the sample was available. Operating problems with the oven used to maintain the temperature of the material caused early curtailment of one test.

The compaction temperature of the mix was 250 degrees Fahrenheit. This temperature was selected so as to be consistent with two procedures that are recognized at the national level, MIL-STD-620A (3) of the Department of Defense and the Federal Aviation Administration Eastern Region Laboratory Procedures Manual (4). Another factor influencing the

Table VII. Target Weights for Specimens

Height (in)	Weight (grams)
2.0	960
2.0	976
2.0	992
2.1	1008
2.1	1024
2.1	1040
2.2	1056
2.2	1072
2.2	1088
2.3	1104
2.3	1120
2.3	1136
2.4	1152
2.4	1168
2.4	1184
2.5	1200
2.5	1216
2.5	1232
2.6	1248
2.6	1264
2.6	1280
2.7	1296
2.7	1312
2.7	1328
2.8	1344
2.8	1360
2.8	1376
2.9	1392
2.9	1408
2.9	1424
3.0	1440
3.0	1456
3.0	1472

decision to use 250 degrees was the fact that the South Carolina Highway Department has a designated compaction temperature of 290 degrees Fahrenheit. As a result, the appropriate viscosity-temperature curves which are used to determine the compaction temperature under MS-2, the standard procedure published by the Asphalt Institute (2), and ASTM D1559, the standard procedure published by the American Society for Testing and Materials (5), were not available.

A mechanical hammer was utilized to prepare the specimens. The machine was a PMC4 Compactor manufactured by Pine Instrument Company. The same hammer was used throughout the experiment.

The face of the hammer and the mold assembly were heated to a temperature of 250 degrees Fahrenheit. The molds were maintained in an oven. A hot plate was used to heat the hammer.

A standard paper protection disk was placed into the heated mold assembly and the mixture of the appropriate target weight was introduced. The temperature of the mixture was monitored with a dial thermometer until it had cooled to the compaction temperature. At that time, the specimen was spaded vigorously with a heated spatula 15 times around the perimeter and ten times over the interior. The surface was smoothed and a paper disk was placed over the specimen.

Fifty blows were applied to both faces of each specimen. The paper disks were removed and specimens were allowed to cool in air to a temperature where they could be comfortably handled. They were then extruded from the molds using a hydraulic press.

Determination of Specimen Height

The remainder of each test was performed on the day immediately following the compaction phase.

The first step was the determination of specimen height. This was accomplished by following the procedures of ASTM D2726, "Standard Test Method for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens" (7).

Initially, a determination of approximate height was made by direct measurement using a steel gauge accurate to 1/1000 inch. However, because it is characteristic of many specimens that the opposing flat faces are not parallel, this measurement was useful only as a check on subsequent calculations.

In accordance with ASTM D2726, each specimen was weighed in air. Then, it was submerged in 77 degree Fahrenheit water for a period of 3 minutes. The weight of the submerged specimen was recorded at the end of that period. The specimen was then removed from the water, its surface was immediately blotted dry with a towel, and its weight was recorded. This data allowed the calculation of volume, height, and specific gravity. All weights were obtained with a 4000 gram capacity electronic balance that was accurate to 0.1 grams.

Specimens that were greater than 3.0 inches in height were discarded because of the limitations of the 3.0 inch wide testing head. Specimens of less than 2.0 inches in height were retained for testing.

Stability and Flow Test

After the specimen height and specific gravity were measured, the stability and flow test was performed. The specimens were placed in a

140 degree Fahrenheit water bath for a period of 30 minutes. The Marshall testing head was maintained at a temperature of 90 degrees by a water bath. Every specimen was placed in the testing head and loaded to failure using a testing machine having an automatic load and deformation recorder. The machine was a 850 Test Press manufactured by Pine Instrument Company. The same testing machine and testing head were used for all testing.

Specimens were selected at random and placed in the water bath in sets of six. The specimens were tested in random order. At no time was a specimen allowed to stay in the water bath more than 40 minutes.

Linear Regression Analysis

The test procedure yielded approximately 33 observations of stability and flow for specimens of varying heights from 2.0 to 3.0 inches. For each mix, a simple linear regression analysis produced prediction lines for stability and flow based on specimen height.

CHAPTER IV

EXPERIMENTAL RESULTS

The experimental data for each of the five mixes are presented in Appendix A. In this chapter, all tests for statistical significance are made at the 5 percent level of significance ($\alpha = .05$). Statistical analysis was performed using SAS (Statistical Analysis System) (10).

Analysis of Stability Results

A highly significant correlation between specimen height and stability was observed to exist for each of the mixes tested. A slope and intercept describing a linear regression line were calculated for each mix. These estimates and the coefficient of determination, r^2, a measure of correlation, appear in Table VIII. A t-test of each of the regression coefficients showed them to be statistically significant. The observed stability values resulting from the analysis of each of the five mixes are presented in graphical form in Appendix B.

The linear regression lines for the stability response were converted to correction lines corresponding to the line of inverse correlation ratios that was derived from the published correction method. This was accomplished by dividing the intercept and slope of the regression line by the standard stability of a 2.5 inch specimen (S_{std}). The standard value used was the value predicted by the regression equation at a height of 2.5 inches. By dividing the slope and the intercept of the regression line by the standard stability, a function was defined which had as its ordinate the ratio of the stability at any

specimen height to the stability of a standard 2.5 inch specimen. This can be demonstrated by dividing both sides of the equation for the regression line by S_{std}, such that

$$S_x/S_{std} = (a/S_{std}) + (b/S_{std})x \tag{4.1}$$

where

S_x = stability value at any height x,

S_{std} = stability of a 2.5 inch high specimen,

a = regression intercept,

b = regression slope,

x = specimen height.

The calculation of the correction line parameters for individual mixes is presented in Table VIII. It can be observed that the slope of the stability correction lines of each of the mixes was less than the slope value, 0.6405, of the published method.

In order to estimate the parameters of a stability correction line with acceptable precision and confidence, it was desirable to combine the data of all five tests into a single linear regression model. Therefore, it was necessary to standardize the stability readings of the separate mixes to permit the pooling of data. To this end, the standard stability value for each mix (S_{std}) was estimated by calculating the stability ordinate at a 2.5 inch height. A stability ratio (SR), shown in Appendix A, equal to the ratio of the stability reading to the standard stability was calculated for each observation such that

$$SR = S_x/S_{std}.$$

Table VIII. Summary of the Linear Regression Analysis of Stability and Calculation of Stability Correction Line Parameters for Each of the Five Mixes Tested

		Regression Line		Correction Line			
Mix	N**	a*	b*	S_{std}*	a/S_{std}	b/S_{std}	r^2
1	34	-1454.1	1689.0	2768	-0.525	0.610	0.662
2	41	-791.2	1389.1	2681	-0.296	0.518	0.627
3	23	-193.3	731.7	1636	-0.118	0.447	0.537
4	33	-312.3	1090.2	2413	-0.129	0.452	0.548
5	35	-727.2	1460.3	2924	-0.249	0.499	0.646

* Refer to Equation 4.1

** Number of observations

A prerequisite for combining the results of different tests into one regression model is a condition of homogeneity of regression lines. This requires that there be no statistically significant difference between the intercepts and slopes of the different regression lines. Prior to pooling the stability ratios (SR) of the five tests into one regression model, a test for homogeneity was performed to determine if the regression lines of any of the mixes differed significantly from the other mixes. The test for homogeneity consisted of an analysis of covariance. The analysis of covariance is presented in Table IX.

In the analysis of covariance model, the sum of squares for the height variable is due to a simple linear regression of stability ratio on height ignoring the groupings by mix and is statistically significant. The sum of squares for the class variable, mix, is due to

different intercepts for the separate mixes, assuming a single regression relationship. The sum of the squares for the interaction term, height by mix, is due to different regression coefficients for the classes specified by mix. Since the probabilities of exceeding the F statistic for the class variable and the interactive term exceed 0.05, there are no significant differences in the regression lines of the separate mixes at the 5 percent level of significance.

Table IX. Analysis of Covariance for the Test for Homogeneity of the Regressions of the Stability Ratio Data Resulting from Separate Tests

Source	df[a]	SS[b]	MS[c]	F[d]	PR>F[e]
Height	1	3.96994102	3.96994102	254.94	0.0001
Mix	4	0.00016722	0.00004181	0.003	1.0000
Height by Mix	4	0.04827110	0.01206778	0.748	0.5610
Error	156	2.51818663	0.01614222		
Total	165	6.53656597			

(a) degrees of freedom

(b) sum of squares

(c) mean square

(d) F test statistic

(e) probability of exceeding the F test statistic

Having established that homogeneity within the correction line results of the five experiments existed, all of the observed stability ratios of the separate experiments were pooled and a regression analysis was performed. The regression analysis resulted in the calculation of statistically significant estimates for the regression parameters. The results of this procedure are included in Table X. A plot of the combined stability ratio data is presented in Figure 6. This figure illustrates the regression line which has the ratio of the stability at any specimen height to the standard stability as its ordinate.

The experimental correction line was compared to the correction line that was representative of the published correction methods. A t-test, shown in Table XI, for homogeneity of the experimental regression coefficient and the slope derived from the published method affirmed that a statistically significant difference did exist between the experimental slope and the published slope. The null hypothesis that the slope equals 0.641, was rejected because the test statistic, $|t_o|$, was greater than the critical t_c, 1.96, with 164 degrees of freedom at the 5 percent level of significance. This disparity is demonstrated in Figure 7.

Table X. Stability Correction Line Parameter Estimates Using the Combined Data of Five Mixes

N	a	b	r^2
166	-0.2707	0.5082	0.607

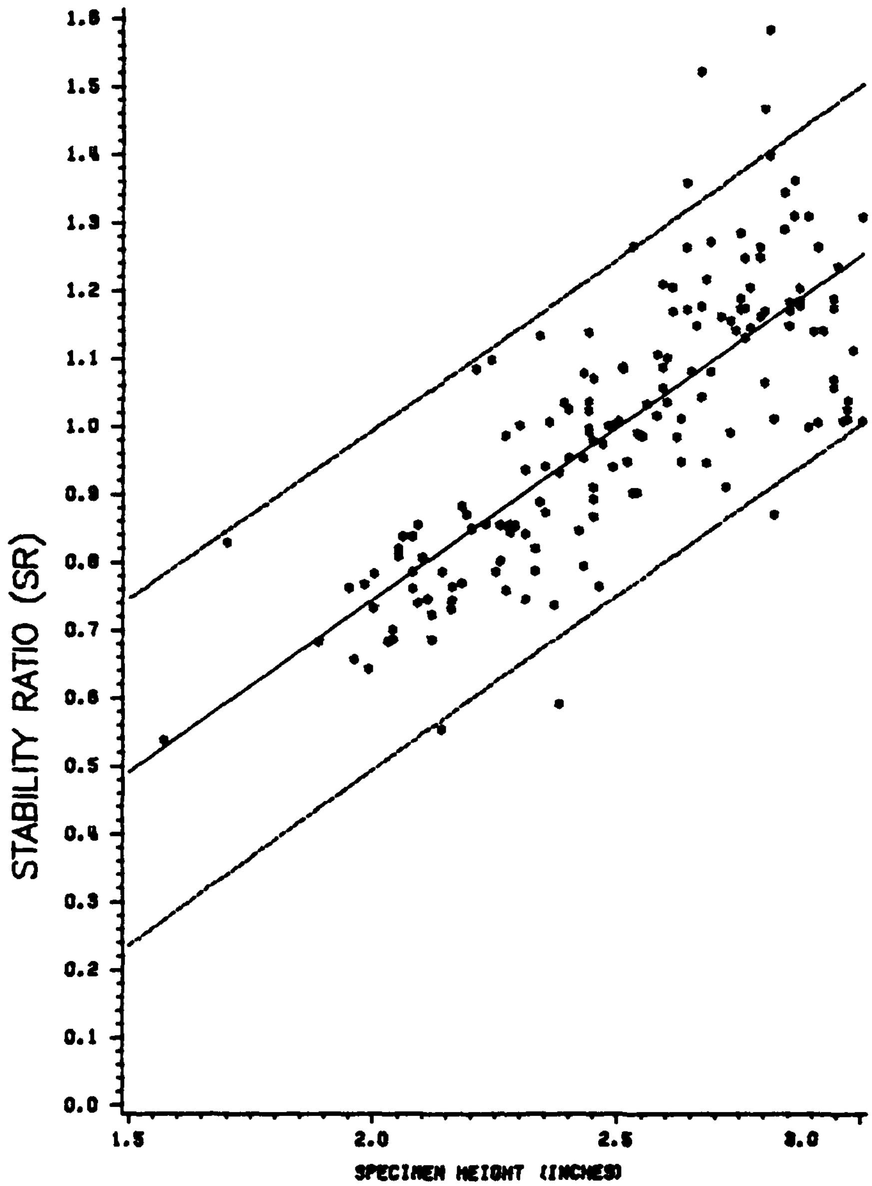


Figure 6. Combined Stability Ratio Data (SR) of the Five Tests with the Resulting Regression Line and 95 Percent Prediction Limits for Individual Observations

Table XI. t-Test for Homogeneity of the Experimental Regression Slope and the Slope of the Published Method

N	b	s_b [a]	β [b]	$\lvert t_o \rvert$ [c]	t_c [d]
166	0.5082	0.0319	0.6405	4.147	1.96

(a) standard deviation of the regression line slope

(b) accepted value for regression line slope

(c) $\lvert t_o \rvert = (\beta - b)/s_b$

(d) $t_c = t_{(.025,164)}$

Analysis of Flow Results

Each of the mixes studied demonstrated that a strong relationship between Marshall flow and specimen height existed. This is emphasized by the relatively high coefficients of determination and the fact that significant regression coefficients were observed. The observed flow values resulting from the analysis of each of the five mixes are presented in graphical form in Appendix C.

As for stability, the flow regression lines were converted to correction lines by dividing the regression parameters by the standard flow value of each mix (F_{std}). These calculations and the estimates of the regression parameters are included in Table XII.

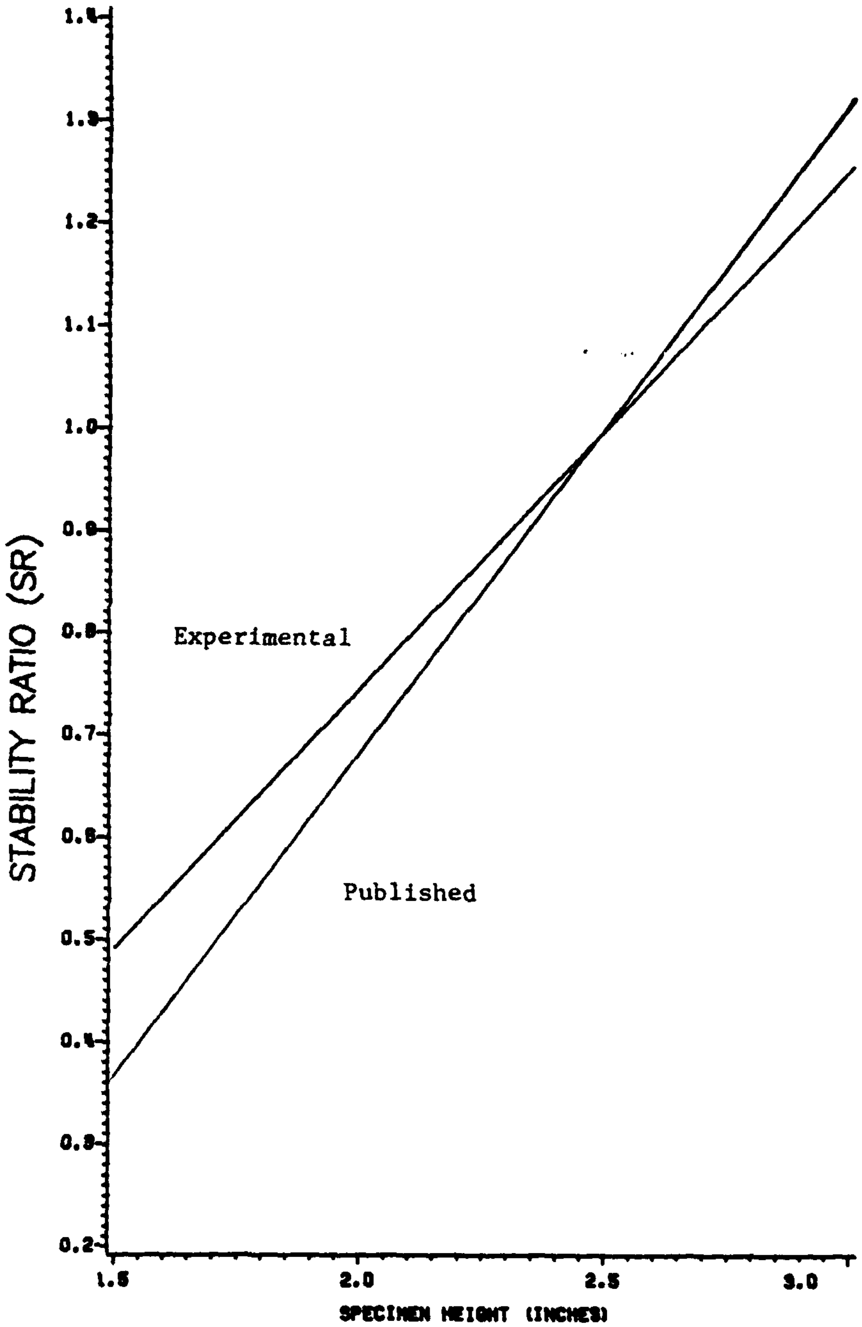


Figure 7. Comparison of the Stability Correction Line Slope of the Published Method with the Experimentally Derived Correction Line

Table XII. Summary of the Linear Regression Analysis of Flow and Calculation of Flow Correction Line Parameters for Each of the Five Mixes Tested

		Regression Line			Correction Line		
Mix	N	a	b	F_{std}	a/F_{std}	b/F_{std}	r^2
1	34	-0.355	5.297	12.89	-0.028	0.411	0.817
2	41	0.458	4.694	12.08	0.038	0.385	0.792
3	23	0.076	3.694	9.31	0.008	0.397	0.596
4	33	-0.820	5.200	12.18	-0.067	0.426	0.768
5	35	-3.148	6.523	13.16	-0.239	0.496	0.812

With the objective of calculating the parameters of the flow correction line using the pooled data from 5 mixes, a test for the homogeneity of the regression lines of flow ratios of the separate experiments was conducted. Flow ratios (FR), shown in Appendix A, were calculated by dividing all flow observations (F_x) by the standard flow value (F_{std}) such that

$$FR = F_x/F_{std} .$$

As for stability, the test for homogeneity consisted of an analysis of covariance. The F statistics for the interactive term, height by mix, and the class variable, mix, were not significant. From this analysis, it was concluded that no statistically significant difference existed between the regression lines of any of the mixes. The analysis of covariance is presented in Table XIII.

Table XIII. Analysis of Covariance for the Test for Homogeneity of the Regressions of the Flow Ratio Data Resulting from Separate Tests

Source	df	SS	MS	F	PR>F
Height	1	2.74963659	2.74963659	523.22	0.0001
Mix	4	0.00002431	0.0000061	0.00	1.0000
Height by Mix	4	0.02376436	0.00594109	1.13	0.3442
Error	156	0.81981041	0.00525519		
Total	165	3.59323566			

Because statistical homogeneity within the regression lines of the flow ratios of each of the five mixes was verified, all flow ratios were combined into a single linear regression model. This procedure resulted in the calculation of statistically significant estimates for the regression line parameters and is summarized in Table XIV.

Table XIV. Flow Correction Line Parameter Estimates Using the Combined Data of Five Mixes

N	a	b	r^2
166	-0.0576	0.4230	0.765

The function defined by the regression line of flow ratios corresponds to a flow correction line. The ordinates of the function equal the ratio of the flow at any specimen height to the flow of the standard 2.5 inch specimen. Figure 8 illustrates the flow ratio observations and the resulting regression line.

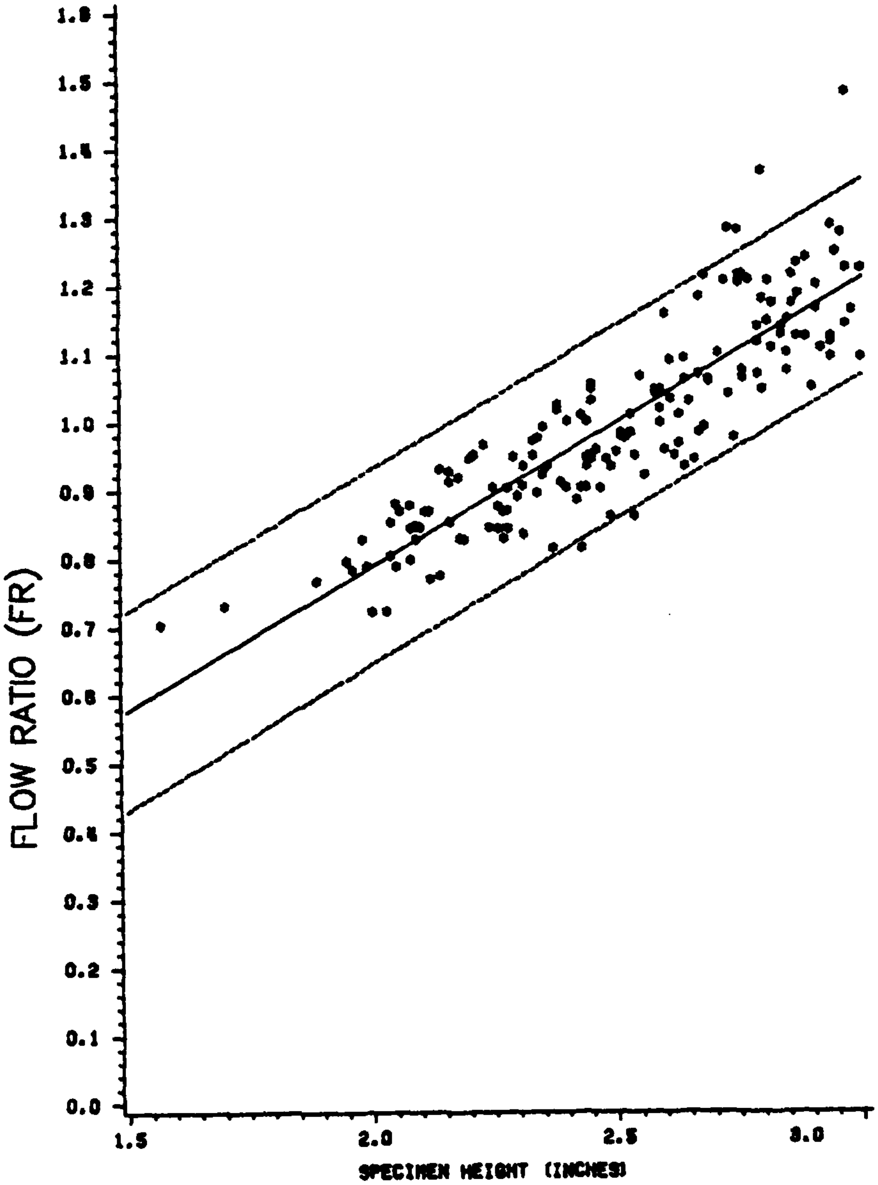


Figure 8. Combined Flow Ratio Data (FR) of the Five Tests with the Resulting Regression Line and 95 Percent Prediction Limits for Individual Observations

Analysis of Air Void Content

Having established the existence of a height effect on stability and flow, it was desirable to investigate further into the dynamics of the mechanism causing the observed behavior of the stability and flow responses. Considering the constant amount of compactive effort that was applied to each specimen by the hammer, it was anticipated that increases in specimen height could be accompanied by decreases in bulk density and a corresponding increase in the percentage of air voids. This effect seemed feasible since a constant compactive effort was applied to a variable mass of material. It was hypothesized that the percentage of air voids would increase as specimen height increased.

In order to test that hypothesis, a linear regression model in which the percentage of air voids was dependent upon specimen height was analyzed using the data from each mix. The regression slope was statistically significant at the 5 percent level for all but Mix 1. However, the coefficients of determination, a measure of correlation, were relatively low, suggesting the presence of other variables contributing to the air void content in addition to the height variable. Small regression slopes suggested that specimen height had little practical impact on air void content. The estimates of the regression parameters are presented in Table XV.

Table XV. Summary of the Linear Regression Parameter Estimates for Air Void Content as a Function of Height

Mix	N	a	b	r^2
1	34	1.50	0.599	0.07
2	41	2.59	0.985	0.15
3	23	4.69	0.765	0.29
4	33	1.34	1.199	0.48
5	35	3.11	1.019	0.16

The relationship between flow and air voids was also investigated as a possible source of information about the flow response. It was hypothesized that increases in flow at the higher specimen height were caused in part by higher air void contents. To test this hypothesis, a linear regression analysis with flow as a function of air void content was performed. The regression slopes of all of the mixes were statistically significant at the 5 percent level, however, the coefficients of determination and slope values were relatively low. This indicated the presence of other contributors to the flow response and was consistent with the high correlation between flow and height. The estimates of the regression line parameters are presented in Table XVI.

Table XVI. Summary of the Linear Regression Parameter Estimates for Flow as a Function of Air Void Content

Mix	N	a	b	r^2
1	34	9.67	1.070	0.17
2	41	8.65	0.676	0.11
3	23	-3.65	1.976	0.34
4	33	2.84	2.138	0.39
5	35	4.27	1.569	0.31

The low correlation of air void content to flow led to the conclusion that air void content had little impact on the flow response. The low correlation of air void content to specimen height led to the conclusion that height had little influence on air void content. This evidence did not support the hypothesis that variations in the amount of compaction achieved caused variations in bulk density and air void content. Further, this information did not support the hypothesis that flow values were dependent on the air void content caused by variations in bulk density. In summary, there was no evidence linking higher deformations at large specimen heights to variations in the amount of compaction that was achieved during the preparation of the specimen.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The experimental results presented in this study represent the testing of five asphaltic concrete mixtures produced within a single geographic area. This small sampling cannot be used as the sole basis of a definitive correction method having application for the infinite number of materials that are available. However, the results of this study may be used as a basis for suggesting the implementation of a correction method which improves on current practices. A new method must conform more closely to the exhibited response of Marshall properties to variations in specimen height. It should provide a greater degree of engineering conservatism than has heretofore been the case.

Stability Correction Procedure

The results of this study indicate a high correlation between specimen height and Marshall stability readings. This finding supports the concept of linear adjustment that is presented in the published testing procedures.

The table of correlation ratios that is presented in published testing procedures is not consistent with the experimental results of this study. The application of the published correction method to each of the mixes tested would have yielded inaccurate estimates.

To illustrate the magnitude of the inaccuracy, tables which are representative of the published method and the experimental results should be considered. These tables are presented at the end of this

chapter. A comparison of the published stability correction ratio with the observed ratio at a height of 2.0 inches is useful. The published correlation ratio, the ratio of the standard stability to the stability of a 2.0 inch specimen, is 1.47 (Table I). The published stability correlation ratios are reproduced in Table XVII. The experimental correlation factor is the inverse of 0.746, the ordinate of the stability correction line at a 2.0 inch height (Figure 6). This value is 1.34. The experimental stability correction line ordinates derived from Figure 6 are presented as correction factors in Table XVIII. The ratio of the published correlation ratio to the experimental ratio is 1.097. Therefore, given a stability reading at 2.0 inches, the standard stability value obtained from the published method will exceed the value equal to the product obtained using the experimental ratio by 9.7 percent of the experimental standard stability.

Consideration of an overlarge specimen further demonstrates the degree of inaccuracy. The published correlation ratio for a 3.0 inch specimen is 0.76. The experimental ratio is the inverse of 1.25, the ordinate of the stability correction line at a 3.0 inch height. This value is 0.80. The ratio of the published correlation ratio to the experimental ratio is 0.95. Given a stability reading at a height of 3.0 inches, the standard value obtained using the published method will be 95 percent of the value obtained using the experimental ratio, for a 5 percent difference. It is clear that inaccuracies of this magnitude may not reflect a true appraisal of the quality of the tested material.

This analysis of the stability test results leads to the conclusion that while a correction method based on a linear stability response is

appropriate for the mixes tested, the slope of the published correction line is too high, resulting in inaccurate estimates. As demonstrated, this problem is crucial for specimen heights in the interval from 2.0 to 2.5 inches, because it results in a significant overestimate of the standard stability value. This suggests that the correction line slope should be adjusted so as to more accurately reflect the stability response to variations in specimen height. Due to the limited scope of the materials considered in this study, a more thorough study should be initiated with the objective of determining variations in the stability correction line parameters that occur as a result of differences in the component materials of the asphaltic concrete mixture. This would facilitate the estimation of correction line parameters applicable to a wide spectrum of materials with a greater degree of confidence.

Table XVIII is an example of a stability correlation ratio table that is based on the correction line parameter estimates of this study. Included are the ordinates of the correction line at incremental specimen heights and the corresponding correlation ratios which are the inverse of the correction line ordinates.

Flow Correction Procedure

The flow test results of this study confirm a high correlation between specimen height and Marshall flow readings. This finding suggests that it is appropriate to utilize a correction method similar to that used for stability to adjust for variations in specimen height.

The current practice of ignoring variations in specimen height results in inaccuracies that prevent the accurate appraisal of the flow qualities of a mix. The experimental correction line ordinates derived

from Figure 8 are presented as correction factors in Table XIX at the end of this chapter.

For a 2.0 inch high specimen, the inverse of the ordinate at 2.0 inches of the regression line, 1.27, indicates the need for a 27 percent increase in the flow reading. At 3.0 inches, the inverse of the ordinate at 3.0 inches of the regression line, 0.83, indicates that a 17 percent reduction in the reading is appropriate. Further, the correction ratios determined in this study corresponding to 2.0 and 3.0 inches, 0.79 and 1.21 respectively, indicate that the actual flow readings taken at the extreme heights of 2.0 and 3.0 inches differ from the standard flow by 21 percent of the standard flow value. Variation by this amount requires the standardization of flow values in order to reflect a meaningful appraisal of the flow properties of the material.

It is recommended that a correction procedure utilizing tabular correlation ratios derived from the flow correction line be implemented. Such a table is presented in Table XIX.

Table XVII. Stability Correlation Ratios as Published by the Asphalt Institute (2)

Volume of specimen (cu cm)	Height (in)	Correlation Ratio
406-420	2	1.47
421-431	2 1/16	1.39
432-443	2 1/8	1.32
444-456	2 3/16	1.25
457-470	2 1/4	1.19
471-482	2 5/16	1.14
483-495	2 3/8	1.09
496-508	2 7/16	1.04
509-522	2 1/2	1.00
523-535	2 9/16	0.96
536-546	2 5/8	0.93
547-559	2 11/16	0.89
560-573	2 3/4	0.86
574-585	2 13/16	0.83
586-598	2 7/8	0.81
599-610	2 15/16	0.78
611-625	3	0.76

Table XVIII. Stability Correlation Ratios Based on Experimental Results

Volume (cu cm)	Height (in)	Correction Factor	Correlation Ratio
406-420	2	.746	1.34
421-431	2 1/16	.778	1.29
432-443	2 1/8	.809	1.23
444-456	2 3/16	.841	1.19
457-470	2 1/4	.873	1.15
471-482	2 5/16	.905	1.10
483-495	2 3/8	.936	1.07
496-508	2 7/16	.968	1.03
509-522	2 1/2	1.000	1.00
523-535	2 9/16	1.032	.97
536-546	2 5/8	1.063	.94
547-559	2 11/16	1.095	.91
560-573	2 3/4	1.127	.89
574-585	2 13/16	1.159	.86
586-598	2 7/8	1.190	.84
599-610	2 15/16	1.222	.82
611-625	3	1.254	.80

Table XIX. Flow Correlation Ratios Based on Experimental Results

Volume (cu cm)	Height (in)	Correction Factor	Correlation Ratio
406-420	2	.788	1.27
421-431	2 1/16	.814	1.23
432-443	2 1/8	.841	1.19
444-456	2 3/16	.868	1.15
457-470	2 1/4	.894	1.12
471-482	2 5/16	.921	1.09
483-495	2 3/8	.947	1.06
496-508	2 7/16	.974	1.03
509-522	2 1/2	1.000	1.00
523-535	2 9/16	1.026	0.97
536-546	2 5/8	1.053	0.95
547-559	2 11/16	1.079	0.93
560-573	2 3/4	1.106	0.90
574-585	2 13/16	1.132	0.88
586-598	2 7/8	1.159	0.86
599-610	2 15/16	1.185	0.84
611-625	3	1.211	0.83

APPENDICES

Appendix A

Experimental Data

Table A-I. Mix 1 Volumetric Data

Obs	Weight in Air (gm)	Weight in Water (gm)	Weight in Air (gm)	Absorption (gm)	Corrected Weight in Water (gm)	Volume (cu cm)
1	984.1	566.7	986.4	1.5	565.2	419.7
2	1437.1	823.7	1438.1	1.0	822.7	614.4
3	1175.9	677.3	1177.1	1.2	676.1	499.8
4	1147.8	659.7	1148.2	.4	659.3	488.5
5	1103.4	636.5	1103.7	.3	636.2	467.2
6	1051.2	607.0	1051.6	.4	606.6	444.6
7	1202.4	693.1	1202.8	.4	692.7	509.7
8	1392.6	802.0	1393.3	.7	801.3	591.3
9	1289.1	745.5	1289.3	.2	745.3	543.8
10	1025.2	593.6	1025.4	.2	593.4	431.8
11	1356.7	783.0	1357.1	.4	782.6	574.1
12	1111.1	643.4	1111.8	.7	642.7	468.4
13	1369.6	790.8	1369.8	.2	790.6	579.0
14	1073.1	623.3	1073.1	.0	623.3	449.8
15	1352.9	776.3	1353.2	.3	776.0	576.9
16	1186.7	684.5	1186.9	.2	684.3	502.4
17	952.0	548.7	952.4	.4	548.3	403.7
18	1216.7	699.6	1217.0	.3	699.3	517.4
19	1386.0	795.7	1386.8	.8	794.9	591.1
20	1311.5	753.3	1311.9	.4	752.9	558.6
21	1014.3	574.8	1014.8	.5	574.3	440.0
22	1423.3	815.5	1423.9	.6	814.9	608.4
23	1282.4	739.0	1283.0	.6	738.4	544.0
24	1295.8	743.4	1296.5	.7	742.7	553.1
25	1176.6	675.2	1177.5	.9	674.3	502.3
26	995.7	572.2	996.5	.8	571.4	424.3
27	1248.1	716.3	1249.0	.9	715.4	532.7
28	1113.2	638.8	1114.1	.9	637.4	475.8
29	1314.3	747.7	1314.6	.3	747.4	566.9
30	1185.1	680.8	1185.8	.7	680.1	505.0
31	1063.6	610.2	1064.0	.4	609.8	453.8
32	1284.8	735.9	1286.6	1.8	734.1	550.7
33	1179.1	674.2	1179.5	.4	673.8	505.3
34	1422.6	811.7	1424.0	1.4	810.3	612.3

Table A-II. Mix 1 Marshall Test Data

Obs	Height (in)	Specific Gravity	Airvoids (%)	Stability (lbs) S_x	Stability Ratio SR	Flow (.01 in) F_x	Flow Ratio FR
1	2.04	2.347	3.14	1900	.6863	11.0	0.8535
2	2.98	2.339	3.47	3080	1.1125	15.0	1.1639
3	2.43	2.353	2.89	2200	.7947	10.5	.8147
4	2.37	2.350	3.01	2040	.7369	10.5	.8147
5	2.27	2.362	2.52	2100	.7586	10.7	.8302
6	2.16	2.364	2.43	2060	.7441	11.0	.8535
7	2.48	2.359	2.64	2770	1.0006	12.2	.9466
8	2.87	2.355	2.81	3330	1.2028	14.5	1.1251
9	2.64	2.371	2.15	3760	1.3582	13.7	1.0630
10	2.10	2.374	2.02	2230	.8055	10.9	.8458
11	2.79	2.363	2.48	3500	1.2643	13.8	1.0708
12	2.27	2.372	2.10	2730	.9861	11.2	.8690
13	2.81	2.365	2.39	3870	1.3979	14.8	1.1484
14	2.18	2.386	1.53	2130	.7694	10.7	.8302
15	2.80	2.345	3.22	2950	1.0656	13.5	1.0475
16	2.44	2.362	2.52	3150	1.1378	12.9	1.0009
17	1.96	2.358	2.68	1820	.6574	10.1	.7837
18	2.51	2.352	2.93	3010	1.0873	12.7	.9854
19	2.87	2.345	3.22	3280	1.1848	15.3	1.1872
20	2.71	2.348	3.10	3220	1.1631	14.2	1.1018
21	2.14	2.305	4.87	1530	.5527	12.0	.9311
22	2.95	2.339	3.47	3420	1.2354	16.1	1.2492
23	2.64	2.357	2.72	3500	1.2643	14.1	1.0940
24	2.69	2.343	3.30	3520	1.2715	13.7	1.0630
25	2.44	2.342	2.34	2760	.9970	12.2	.9466
26	2.06	2.347	3.14	2320	.8380	11.2	.8690
27	2.59	2.343	3.30	3350	1.2101	13.5	1.0475
28	2.31	2.340	3.43	2330	.8416	11.7	.9078
29	2.75	2.318	4.33	3290	1.1884	15.5	1.2027
30	2.45	2.347	3.14	2520	.9103	13.5	1.0475
31	2.20	2.344	3.26	2350	.8489	12.2	.9466
32	2.67	2.333	3.71	2890	1.0439	13.8	1.0708
33	2.45	2.333	3.71	2400	.8669	13.6	1.0553
34	2.97	2.323	4.13	2800	1.0114	15.8	1.2260

Table A-III. Mix 2 Volumetric Data

Obs	Weight in Air (gm)	Weight in Water (gm)	Weight in Air (gm)	Absorption (gm)	Corrected Weight in Water (gm)	Volume (cu cm)
1	1158.3	664.9	1159.0	.7	664.2	494.1
2	1189.7	687.1	1190.5	.8	686.3	503.4
3	1300.5	746.0	1300.7	.2	745.8	554.7
4	1122.8	646.7	1123.0	.2	646.5	476.3
5	1183.7	680.2	1184.2	.5	679.7	504.0
6	1257.3	722.2	1257.9	.6	721.6	535.7
7	1417.6	807.3	1418.5	.9	806.4	611.2
8	1174.7	675.4	1175.4	.7	674.7	500.0
9	1258.1	721.0	1258.6	.5	720.5	537.6
10	1390.0	789.8	1390.9	.9	788.9	601.1
11	1023.2	587.4	1023.6	.4	587.0	436.2
12	1019.9	585.3	1020.2	.3	585.0	434.9
13	1094.3	625.1	1094.6	.3	624.8	469.5
14	766.5	442.5	766.7	.2	442.3	324.2
15	1362.1	772.2	1362.7	.6	771.6	590.5
16	1204.4	684.9	1205.5	1.1	683.8	520.6
17	1169.4	664.3	1169.9	.5	663.8	505.6
18	1307.3	740.2	1307.7	.5	739.7	567.5
19	1337.5	762.4	1337.9	.4	762.0	575.5
20	1056.0	604.7	1056.2	.2	604.5	451.5
21	1239.7	701.4	1240.2	.5	700.9	538.8
22	1358.8	773.5	1359.9	1.1	772.4	586.4
23	1075.4	609.5	1075.7	.3	609.2	466.2
24	1274.2	723.3	1274.8	.6	722.7	551.5
25	1401.7	796.9	1402.5	.8	796.1	605.6
26	1314.4	750.2	1314.9	.5	749.7	564.7
27	1096.9	621.8	1097.2	.3	621.5	475.4
28	1146.4	648.5	1147.2	.8	647.7	498.7
29	1002.9	567.6	1003.5	.6	567.0	435.9
30	1359.9	765.2	1360.5	.6	764.6	595.3
31	1105.0	622.7	1105.8	.8	621.9	483.1
32	1246.3	711.1	1247.0	.7	710.4	535.9
33	1037.1	592.5	1037.9	.8	591.7	445.4
34	1316.8	748.0	1318.0	1.2	746.8	570.0
35	952.1	543.9	952.3	.2	543.7	408.4
36	1428.6	812.6	1429.4	.8	811.8	616.8
37	1367.9	779.3	1368.5	.6	778.7	589.2
38	988.8	562.1	989.4	.6	561.5	427.3
39	1131.1	649.5	1131.7	.6	648.9	482.2
40	1286.4	737.8	1287.1	.7	737.1	549.3
41	1063.8	608.3	1064.2	.4	607.9	455.9

Table A-IV. Mix 2 Marshall Test Data

Obs	Height (in)	Specific Gravity	Airvoids (%)	Stability (lbs) S_x	Stability Ratio SR	Flow (.01 in) F_x	Flow Ratio FR
1	2.40	2.344	4.29	2560	.9547	12.1	1.0016
2	2.44	2.363	3.51	2780	1.0368	11.3	.9354
3	2.69	2.345	4.25	2900	1.0815	12.8	1.0595
4	2.31	2.357	3.76	2510	.9361	11.3	.9354
5	2.45	2.349	4.08	2870	1.0703	11.5	.9519
6	2.60	2.347	4.16	2780	1.0368	11.6	.9602
7	2.97	2.319	5.31	2750	1.0256	13.8	1.1423
8	2.43	2.349	4.08	2890	1.0778	12.2	1.0099
9	2.61	2.340	4.45	3230	1.2046	12.5	1.0347
10	2.92	2.312	5.59	3060	1.1412	13.4	1.1092
11	2.12	2.346	4.21	1840	.6862	9.3	.7698
12	2.11	2.345	4.25	2000	.7459	10.5	.8691
13	2.28	2.331	4.82	2290	.8540	10.2	.8443
14	1.57	2.364	3.47	1440	.5370	8.5	.7036
15	2.87	2.307	5.80	3160	1.1785	14.9	1.2333
16	2.53	2.313	5.55	2420	.9025	11.9	.9850
17	2.46	2.313	5.55	2050	.7645	11.6	.9602
18	2.76	2.303	5.96	3150	1.1748	13.0	1.0761
19	2.79	2.324	5.10	3350	1.2493	13.5	1.1175
20	2.19	2.339	4.49	2330	.8689	10.0	.8278
21	2.62	2.301	6.04	2640	.9846	11.5	.9519
22	2.85	2.317	5.39	3170	1.1822	13.9	1.1506
23	2.26	2.307	5.80	2150	.8018	10.6	.8774
24	2.68	2.310	5.68	2540	.9472	12.0	.9933
25	2.94	2.315	5.47	3150	1.1748	13.5	1.1175
26	2.74	2.328	4.94	3060	1.1412	11.8	.9767
27	2.31	2.307	5.80	2000	.7459	10.1	.8360
28	2.42	2.299	6.12	2270	.8466	10.7	.8857
29	2.12	2.301	6.04	1940	.7235	10.5	.8691
30	2.89	2.284	6.74	2680	.9995	15.0	1.2416
31	2.35	2.287	6.61	2340	.8727	12.0	.9933
32	2.60	2.326	5.02	2950	1.1002	14.0	1.1588
33	2.16	2.328	4.94	1960	.7310	11.2	.9271
34	2.77	2.310	5.68	3230	1.2046	14.6	1.2085
35	1.98	2.331	4.82	2060	.7683	10.0	.8278
36	3.00	2.316	5.43	3510	1.3090	14.8	1.2251
37	2.86	2.322	5.19	3650	1.3612	14.7	1.2168
38	2.08	2.314	5.51	2040	.7608	10.2	.8443
39	2.34	2.346	4.21	3040	1.1337	11.8	.9767
40	2.67	2.342	4.37	4080	1.5216	14.3	1.1837
41	2.21	2.333	4.74	2910	1.0853	11.5	.9519

Table A-V. Mix 3 Volumetric Data

Obs	Weight in Air (gm)	Weight in Water (gm)	Weight in Air (gm)	Absorption (gm)	Corrected Weight in Water (gm)	Volume (cu cm)
1	1142.1	637.7	1142.3	.2	637.5	504.6
2	1217.8	684.8	1218.2	.4	684.4	533.4
3	1249.9	701.6	1250.3	.4	701.2	548.7
4	1197.2	671.1	1197.5	.3	670.8	526.4
5	1372.9	767.5	1373.3	.4	767.1	605.8
6	1162.9	651.2	1163.3	.4	650.8	512.1
7	1069.4	599.6	1069.7	.3	599.3	470.1
8	1103.9	619.3	1104.2	.3	619.0	484.9
9	1237.7	692.7	1238.0	.3	692.4	545.3
10	976.5	547.0	976.8	.3	546.7	429.8
11	1390.4	774.3	1391.1	.7	773.6	616.8
12	1376.6	765.5	1377.2	.6	764.9	611.7
13	1277.6	710.3	1278.0	.4	709.9	567.7
14	1174.5	656.7	1174.8	.3	656.4	518.1
15	1207.2	673.5	1207.7	.5	673.0	534.2
16	1141.3	637.6	1141.7	.4	637.2	504.1
17	1005.0	561.4	1005.4	.4	561.0	444.0
18	1046.9	588.2	1047.1	.2	588.0	458.9
19	965.4	542.6	965.6	.2	542.4	423.0
20	1310.6	734.9	1311.1	.5	734.4	576.2
21	1327.0	742.8	1327.4	.4	742.4	584.6
22	1248.4	696.8	1248.7	.3	696.5	551.9
23	1079.5	605.3	1079.8	.3	605.0	474.5

Table A-VI. Mix 3 Marshall Test Data

Obs	Height (in)	Specific Gravity	Airvoids (%)	Stability (lbs) S_x	Stability Ratio SR	Flow (.01 in) F_x	Flow Ratio FR
1	2.45	2.263	6.87	1460	.8925	8.8	.9451
2	2.59	2.283	6.05	1780	1.0881	9.3	.9988
3	2.66	2.278	6.26	1880	1.1493	8.8	.9451
4	2.56	2.274	6.42	1690	1.0331	8.6	.9236
5	2.94	2.266	6.75	1730	1.0576	10.2	1.0955
6	2.49	2.271	6.54	1640	1.0026	8.7	.9344
7	2.28	2.275	6.38	1380	.8436	8.1	.8699
8	2.35	2.277	6.30	1540	.9414	8.6	.9236
9	2.65	2.270	6.58	1770	1.0820	9.6	1.0310
10	2.09	2.272	6.50	1210	.7397	7.9	.8485
11	3.00	2.254	7.24	1650	1.0087	10.2	1.0955
12	2.97	2.250	7.41	1700	1.0392	13.8	1.4821
13	2.76	2.250	7.41	1850	1.1309	9.9	1.0633
14	2.52	2.267	6.71	1550	.9475	9.1	.9773
15	2.59	2.260	7.00	1730	1.0576	9.5	1.0203
16	2.45	2.264	6.83	1600	.9781	9.6	1.0310
17	2.16	2.264	6.83	1250	.7641	8.5	.9129
18	2.23	2.281	6.13	1400	.8558	9.0	.9666
19	2.05	2.282	6.09	1340	.8192	8.2	.8807
20	2.80	2.275	6.38	2400	1.4671	11.0	1.1814
21	2.84	2.270	6.58	2110	1.2899	10.5	1.1277
22	2.68	2.262	6.91	1990	1.2165	11.3	1.2136
23	2.30	2.275	6.38	1640	1.0026	8.3	.8914

Table A-VII. Mix 4 Volumetric Data

Obs	Weight in Air (gm)	Weight in Water (gm)	Weight in Air (gm)	Absorption (gm)	Corrected Weight in Water (gm)	Volume (cu cm)
1	1017.9	590.8	1019.6	1.7	589.1	428.8
2	1203.9	696.4	1205.8	1.9	694.5	509.4
3	967.3	560.7	970.2	2.9	557.8	409.5
4	1268.6	733.7	1271.5	2.9	730.8	537.8
5	1004.9	583.9	1006.3	1.4	582.5	422.4
6	1110.3	641.5	1111.8	1.5	640.0	470.3
7	1381.6	798.7	1385.6	4.0	794.7	586.9
8	1297.9	752.0	1302.1	4.2	747.8	550.1
9	950.4	550.2	952.5	2.1	548.1	402.3
10	1155.0	667.4	1157.5	2.5	664.9	490.1
11	1404.0	810.2	1408.0	4.0	806.2	597.8
12	1405.3	809.7	1408.8	3.5	806.2	599.1
13	1207.1	696.4	1209.3	2.2	694.2	512.9
14	1129.5	653.7	1132.8	3.3	650.4	479.1
15	1359.6	782.5	1362.6	3.0	779.5	580.1
16	1308.8	753.4	1312.6	3.8	749.6	559.2
17	1335.6	772.1	1339.2	3.6	768.5	567.1
18	1245.4	717.3	1248.4	3.0	714.3	531.1
19	1230.8	710.0	1234.5	3.7	706.3	524.5
20	1056.0	609.2	1057.8	1.8	607.4	448.6
21	1409.5	807.5	1413.0	3.5	804.0	605.5
22	1268.1	728.8	1270.8	2.7	726.1	542.0
23	1346.6	773.9	1353.7	7.1	766.8	579.8
24	1231.7	711.7	1235.2	3.5	708.2	523.5
25	1357.3	781.2	1359.5	2.2	779.0	578.3
26	1090.0	630.9	1092.4	2.4	628.5	461.5
27	981.1	564.1	982.7	1.6	562.5	418.6
28	1319.0	755.7	1321.6	1.7	754.0	565.9
29	1224.9	704.0	1227.3	2.4	701.6	523.3
30	1174.3	675.9	1176.5	2.2	673.7	500.6
31	1375.4	788.6	1378.1	2.7	785.9	589.5
32	839.1	489.2	839.9	.8	488.4	350.7
33	984.8	566.9	987.1	2.3	564.6	420.2

Table A-VIII. Mix 4 Marshall Test Data

Obs	Height (in)	Specific Gravity	Airvoids (%)	Stability (lbs) S_x	Stability Ratio SR	Flow (.01 in) F_x	Flow Ratio FR
1	2.08	2.374	3.42	2020	.8371	10.7	.8785
2	2.47	2.363	3.86	2350	.9738	11.0	.9031
3	1.99	2.362	3.91	1550	.6423	9.6	.7882
4	2.61	2.359	4.03	2820	1.1686	13.3	1.0920
5	2.05	2.379	3.21	1950	.8081	9.6	.7882
6	2.28	2.361	3.95	2050	.8495	11.0	.9031
7	2.85	2.354	4.23	2770	1.1479	13.1	1.0755
8	2.67	2.359	4.03	2840	1.1769	12.0	.9852
9	1.95	2.362	3.91	1840	.7625	9.7	.7964
10	2.38	2.357	4.11	2250	.9324	12.5	1.0263
11	2.90	2.349	4.43	2750	1.1396	12.8	1.0509
12	2.91	2.346	4.56	3050	1.2638	14.2	1.1659
13	2.49	2.353	4.27	2270	.9407	10.5	.8621
14	2.33	2.358	4.07	1900	.7873	11.6	.9524
15	2.82	2.344	4.64	2440	1.0111	13.5	1.1084
16	2.72	2.340	4.80	2200	.9117	14.7	1.2069
17	2.75	2.355	4.19	2830	1.1727	15.6	1.2808
18	2.58	2.345	4.60	2670	1.1064	12.7	1.0427
19	2.55	2.347	4.52	2380	.9863	13.0	1.0673
20	2.18	2.354	4.23	2130	.8827	11.2	.9195
21	2.94	2.328	5.29	2580	1.0691	15.7	1.2890
22	2.63	2.340	4.80	2290	.9490	11.8	.9688
23	2.82	2.323	5.49	2100	.8702	14.3	1.1741
24	2.54	2.353	4.27	2390	.9904	10.5	.8621
25	2.81	2.347	4.52	3820	1.5830	14.7	1.2069
26	2.24	2.362	3.91	2650	1.0981	10.3	.8457
27	2.03	2.344	4.64	1650	.6837	8.8	.7225
28	2.75	2.332	5.13	3100	1.2846	14.8	1.2151
29	2.54	2.341	4.76	2180	.9034	11.6	.9524
30	2.43	2.346	4.56	2300	.9531	11.0	.9031
31	2.86	2.333	5.09	3160	1.3095	14.3	1.1741
32	1.70	2.393	2.64	2000	.8288	8.9	.7307
33	2.04	2.344	4.64	1690	.7003	9.8	.8046

Table A-IX. Mix 5 Volumetric Data

Obs	Weight in Air (gm)	Weight in Water (gm)	Weight in Air (gm)	Absorption (gm)	Corrected Weight in Water (gm)	Volume (cu cm)
1	973.4	562.6	973.8	.4	562.2	411.2
2	1277.1	733.7	1278.2	1.1	732.6	544.5
3	1367.5	782.1	1368.3	.8	781.3	586.2
4	1367.3	783.5	1367.8	.5	783.0	584.3
5	1180.9	678.7	1181.6	.7	678.0	502.9
6	1310.8	748.8	1311.9	1.1	747.7	563.1
7	1416.9	807.7	1417.6	.7	807.0	609.9
8	1419.2	813.6	1419.9	.7	812.9	606.3
9	1207.1	691.3	1208.1	1.0	690.3	516.8
10	1019.8	589.2	1020.1	.3	588.9	430.9
11	1336.6	764.6	1338.5	1.9	762.7	573.9
12	1006.4	577.9	1007.1	.7	577.2	429.2
13	1227.4	707.2	1229.0	1.6	705.6	521.8
14	1138.9	653.2	1139.9	1.0	652.2	486.7
15	1327.8	763.0	1330.7	2.9	760.1	567.7
16	1257.9	718.6	1260.1	2.2	716.4	541.5
17	1084.8	621.0	1085.7	.9	620.1	464.7
18	1102.2	632.6	1103.2	1.0	631.6	470.6
19	1329.0	759.8	1330.5	1.5	758.3	570.7
20	913.6	525.5	914.3	.7	524.8	388.8
21	1165.1	671.5	1165.8	.7	670.8	494.3
22	1238.3	709.2	1240.5	2.2	707.0	531.3
23	1038.3	598.2	1039.1	.8	587.4	440.9
24	1119.1	630.6	1121.6	2.5	628.1	491.0
25	1088.5	626.4	1090.2	1.7	624.7	463.8
26	1391.2	794.9	1394.6	3.4	791.5	599.7
27	1167.7	665.2	1168.5	.8	664.4	503.3
28	1120.9	641.0	1122.9	2.0	639.0	481.9
29	1287.2	726.1	1289.1	1.9	724.2	563.0
30	1383.6	793.1	1387.7	4.1	789.0	594.6
31	960.9	549.7	961.5	.6	549.1	411.8
32	1110.5	631.5	1112.3	1.8	629.7	480.8
33	1328.3	754.8	1330.7	2.4	752.4	575.9
34	1198.4	684.5	1200.2	1.8	682.7	515.7
35	1145.2	653.5	1146.4	1.2	652.3	492.9

Table A-X. Mix 5 Marshall Test Data

Obs	Height (in)	Specific Gravity	Airvoids (%)	Stability (lbs) S_x	Stability Ratio SR	Flow (.01 in) F_x	Flow Ratio FR
1	2.00	2.367	4.29	2290	.7833	9.5	.7219
2	2.64	2.345	5.18	3430	1.1732	12.3	.9347
3	2.85	2.333	5.66	3420	1.1698	14.5	1.1018
4	2.84	2.340	5.38	3930	1.3442	15.0	1.1398
5	2.44	2.348	5.05	2990	1.0227	11.9	.9043
6	2.73	2.328	5.86	3380	1.1561	13.7	1.0410
7	2.96	2.323	6.07	2950	1.0090	16.8	1.2766
8	2.94	2.341	5.34	3470	1.1869	14.8	1.1246
9	2.51	2.336	5.54	3170	1.0843	12.9	.9802
10	2.09	2.367	4.29	2500	.8551	10.9	.8283
11	2.79	2.329	5.82	3400	1.1629	15.0	1.1398
12	2.08	2.345	5.18	2300	.7867	10.5	.7979
13	2.53	2.352	4.89	3700	1.2655	13.3	1.0106
14	2.36	2.340	5.38	2940	1.0056	12.3	.9347
15	2.76	2.339	5.42	3650	1.2484	16.0	1.2158
16	2.63	2.323	6.07	2960	1.0124	13.3	1.0106
17	2.26	2.334	5.62	2500	.8551	11.1	.8435
18	2.29	2.342	5.30	2500	.8551	12.5	.9499
19	2.77	2.329	5.82	3350	1.1458	15.9	1.2082
20	1.89	2.350	4.97	2000	.6841	10.1	.7675
21	2.40	2.357	4.69	3000	1.0261	11.9	.9043
22	2.58	2.331	5.74	2970	1.0159	13.8	1.0486
23	2.14	2.355	4.77	2300	.7867	10.2	.7751
24	2.38	2.279	7.84	1730	.5917	13.4	1.0182
25	2.25	2.347	5.10	2300	.7867	11.9	.9043
26	2.91	2.320	6.19	2940	1.0056	15.8	1.2006
27	2.44	2.320	6.19	2900	.9919	12.5	.9499
28	2.34	2.326	5.94	2600	.8893	11.8	.8967
29	2.73	2.286	7.56	2900	.9919	16.9	1.2842
30	2.89	2.327	5.90	3830	1.3100	14.8	1.1246
31	2.00	2.333	5.66	2140	.7320	9.5	.7219
32	2.33	2.310	6.59	2400	.8209	12.8	.9726
33	2.80	2.306	6.75	3420	1.1698	18.0	1.3678
34	2.50	2.324	6.03	2950	1.0090	12.6	.9575
35	2.39	2.323	6.07	3030	1.0364	12.0	.9119

Appendix B

Observed Stability Values from All Experiments with the Resulting Regression Lines and 95 Percent Prediction Limits for Individual Observations

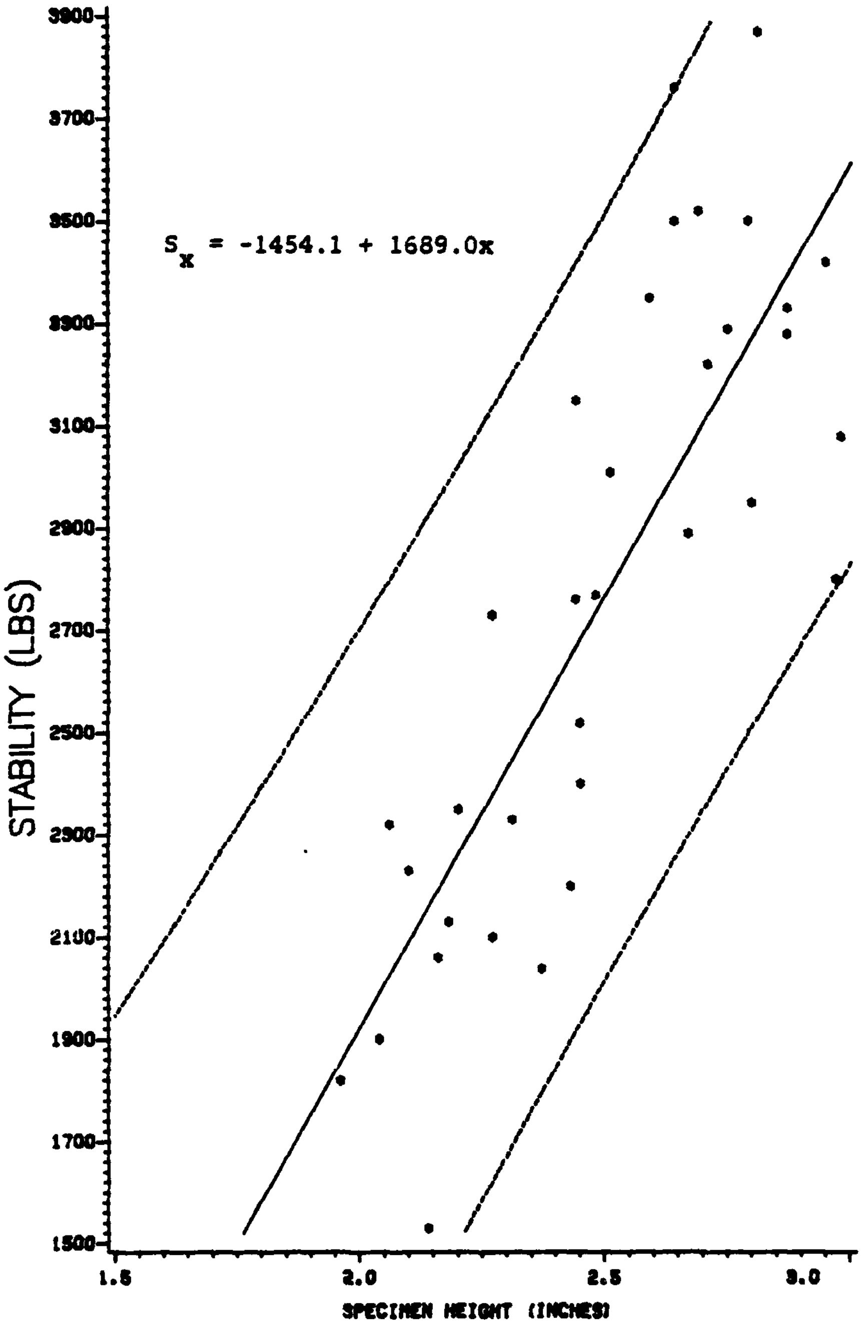


Figure B-1. Mix 1 Stability Observations

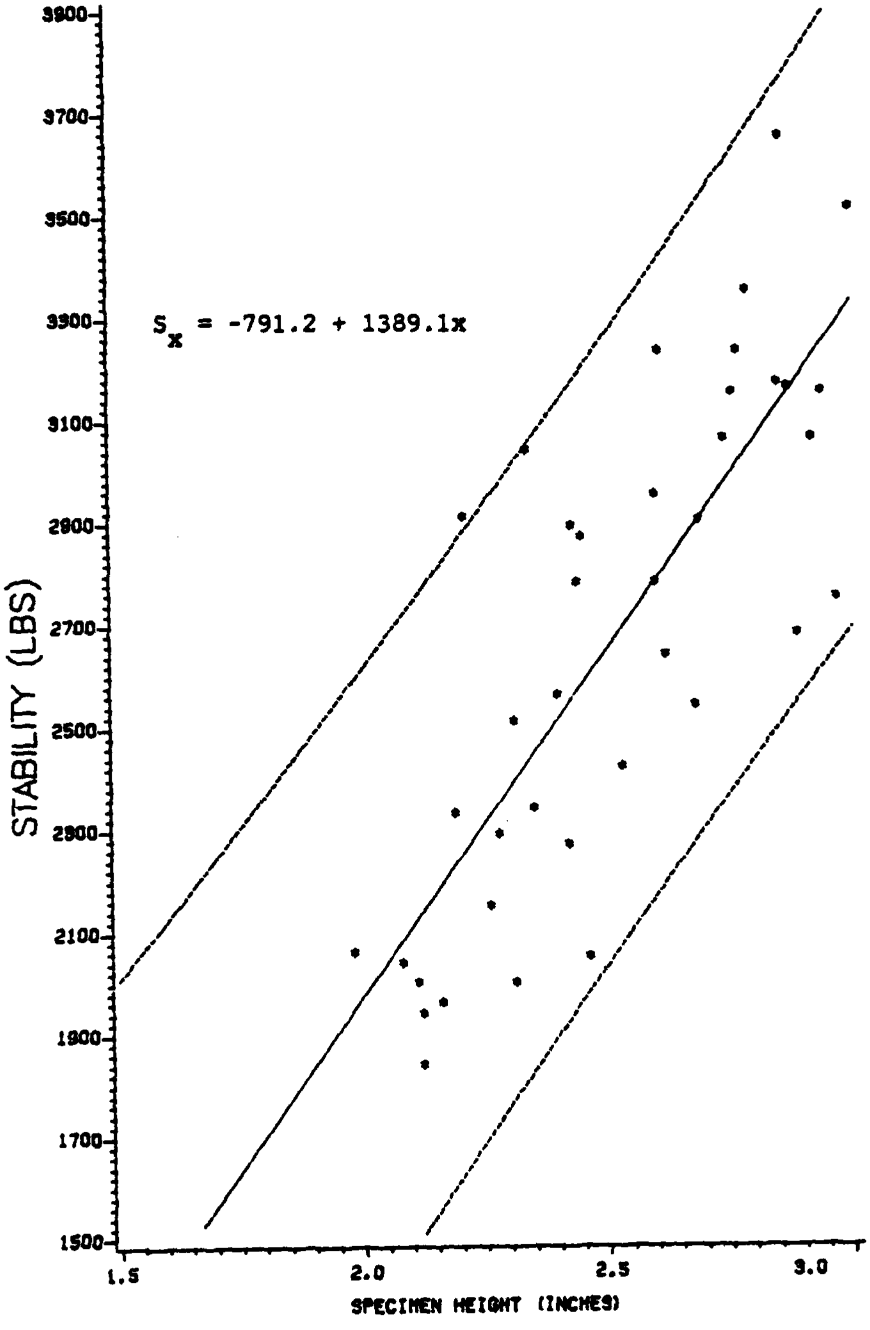


Figure B-2. Mix 2 Stability Observations

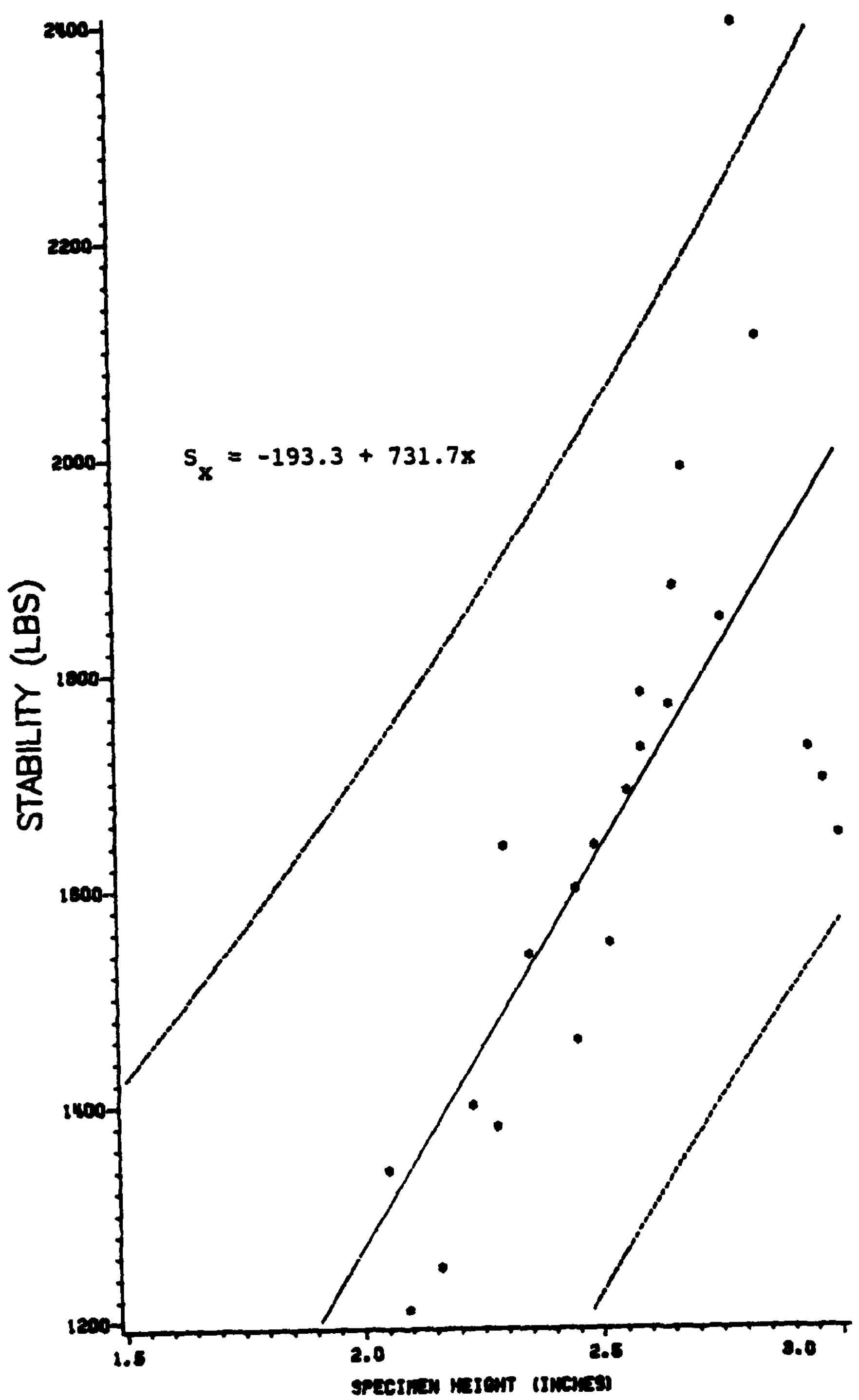


Figure B-3. Mix 3 Stability Observations

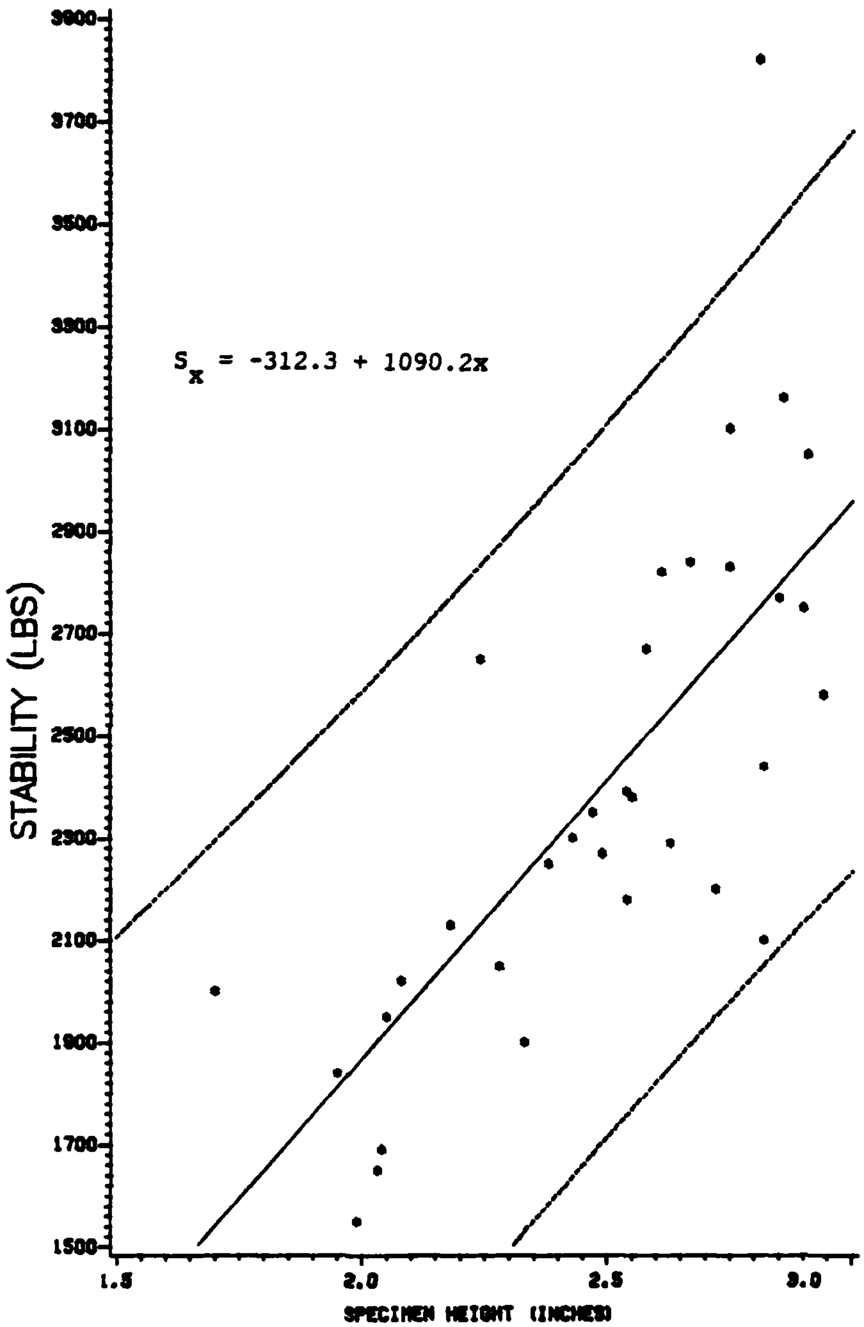


Figure B-4. Mix 4 Stability Observations

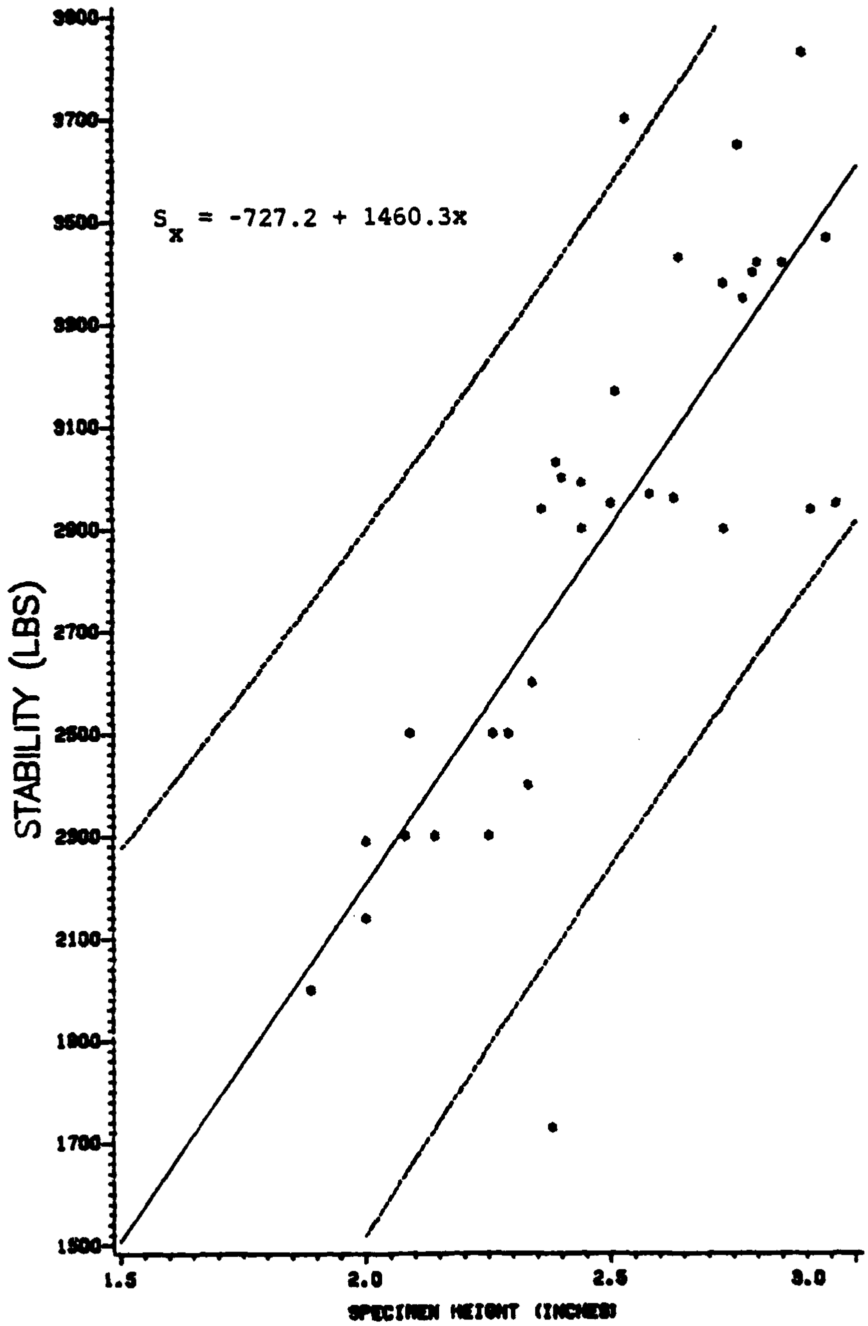


Figure B-5. Mix 5 Stability Observations

Appendix C

Observed Flow Values from All Experiments with the Resulting Regression Lines and 95 Percent Prediction Limits for Individual Observations

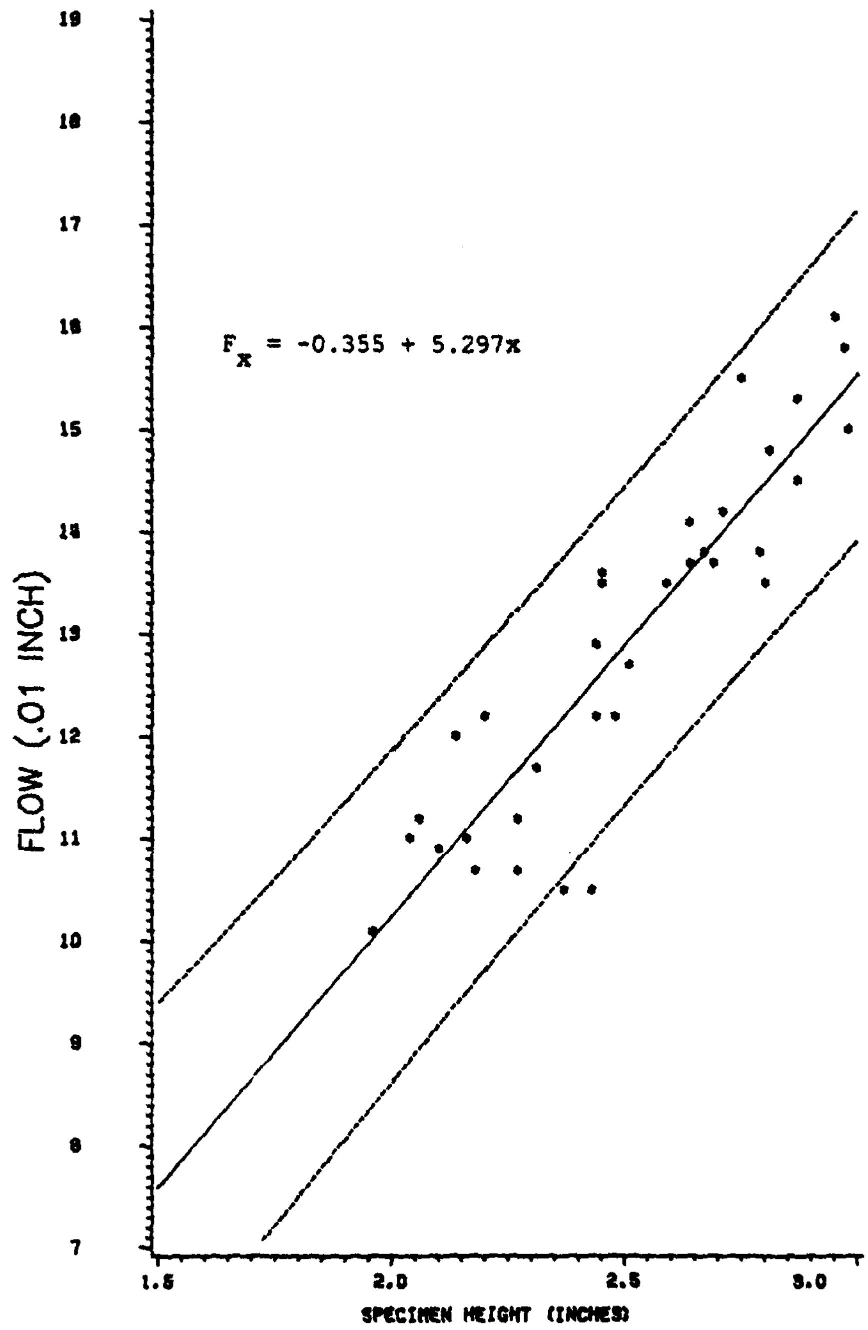


Figure C-1. Mix 1 Flow Observations

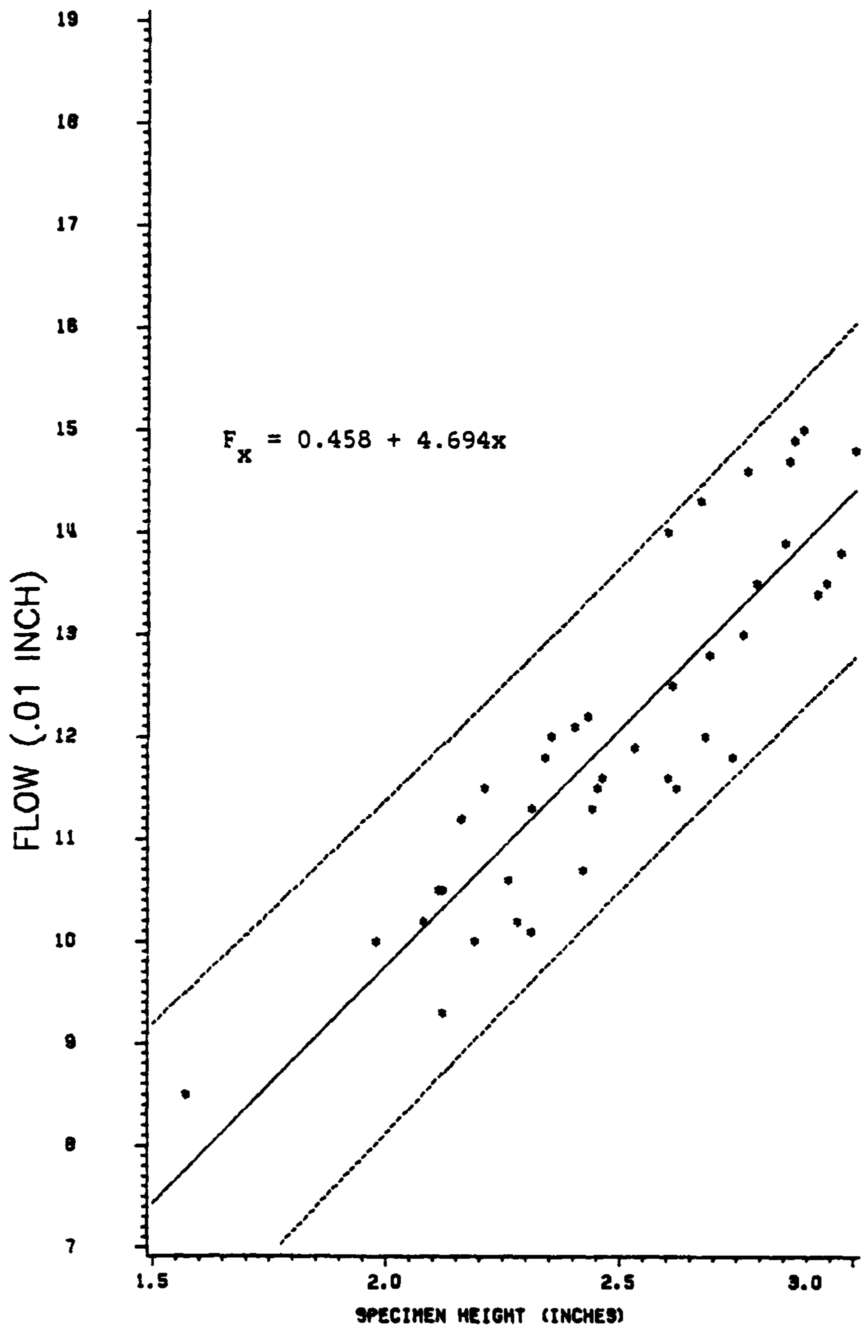


Figure C-2. Mix 2 Flow Observations

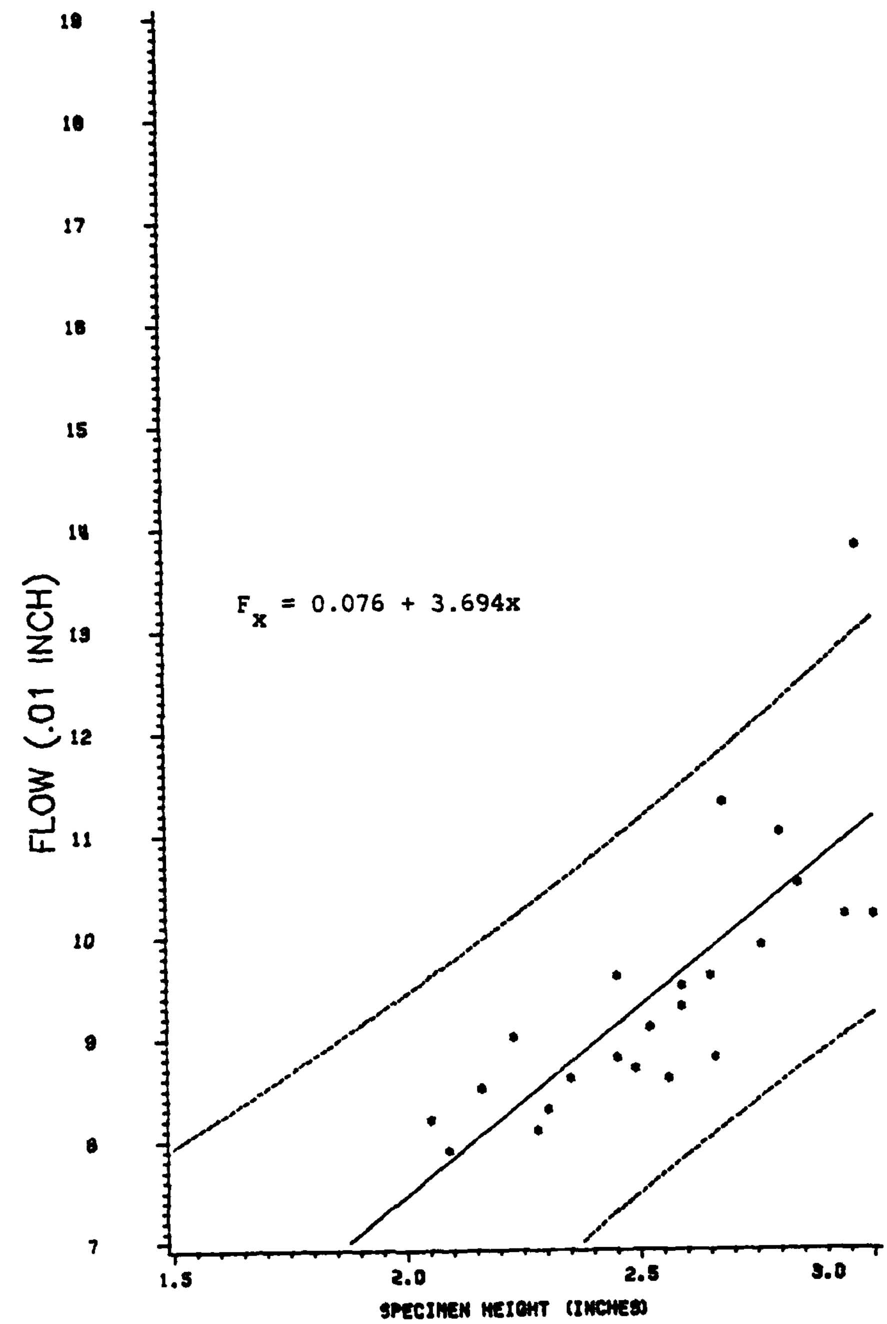


Figure C-3. Mix 3 Flow Observations

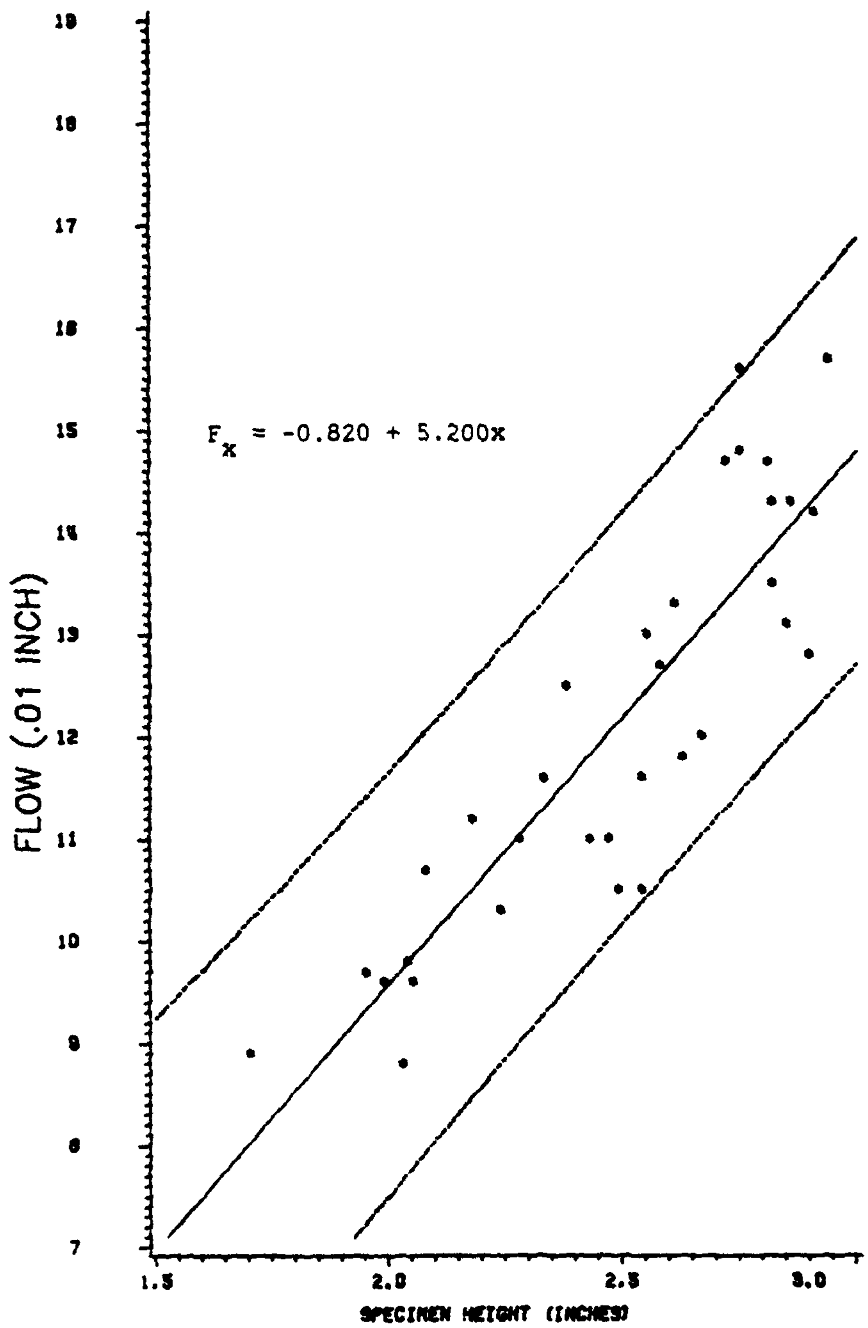


Figure C-4. Mix 4 Flow Observations

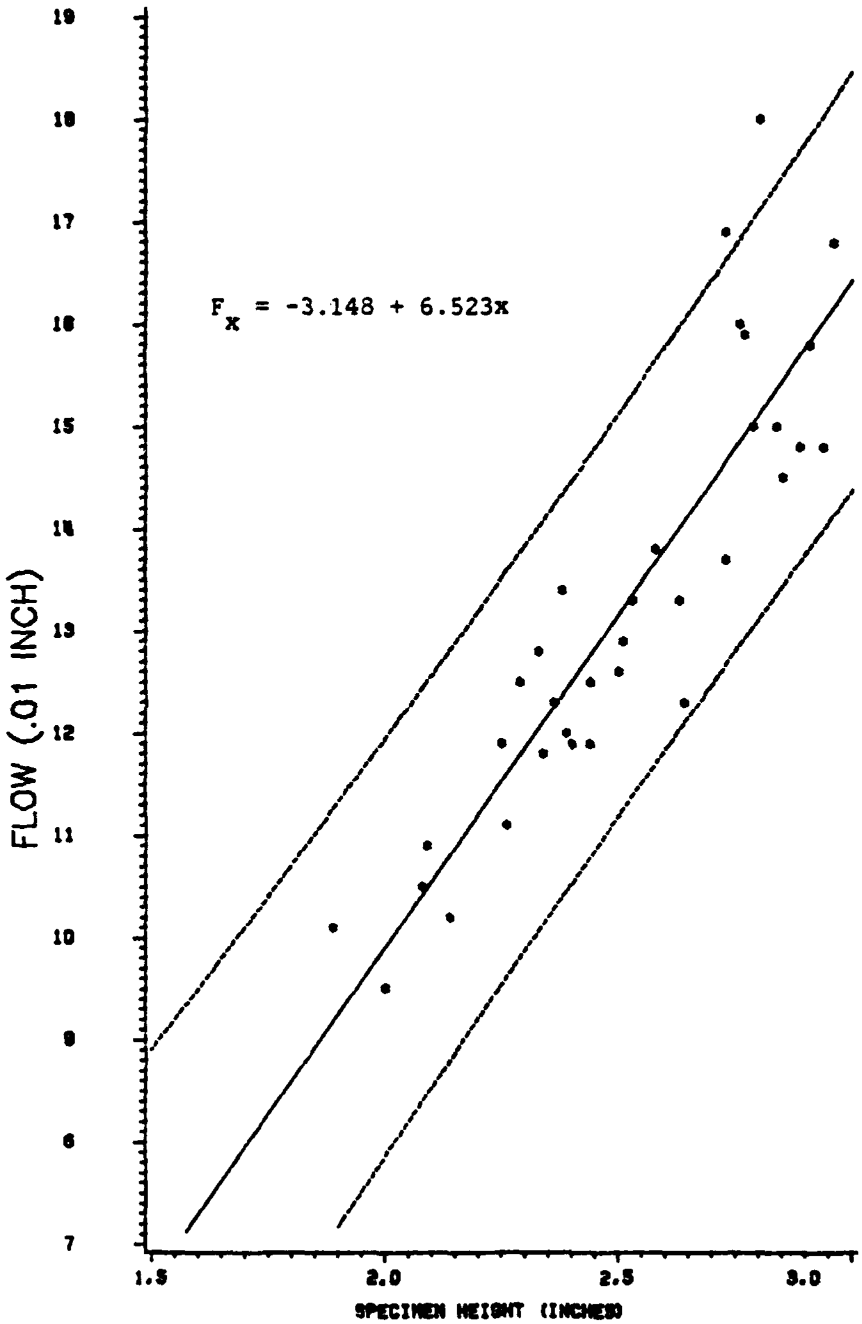


Figure C-5. Mix 5 Flow Observations

Appendix D

Notation

α	statistical level of significance
a	estimate of the intercept parameter of a simple regression line
a/F_{std}	estimate of the intercept parameter of a flow correction line
a/S_{std}	estimate of the intercept parameter of a stability correction line
b	estimate of the slope parameter of a simple regression line
b/F_{std}	estimate of the slope parameter of a flow correction line
b/S_{std}	estimate of the slope parameter of a stability correction line
β	slope parameter of a regression line
df	degrees of freedom
F	F test statistic
FR	flow ratio
F_{std}	flow value of a specimen 2.5 inches in height
F_x	flow value of a specimen at any height x
MS	mean square
N	number of observations
PR>R	probability of an F value greater than the calculated F statistic
R	stability correlation ratio
r^2	coefficient of determination
s_b	standard deviation of the regression slope
SR	stability ratio
SS	sum of squares

S_{std}	stability value of a specimen 2.5 inches in height
S_x	stability value of a specimen at any height x
t_c	critical t value
$\|t_o\|$	test statistic for two tailed t-test
x	specimen height

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